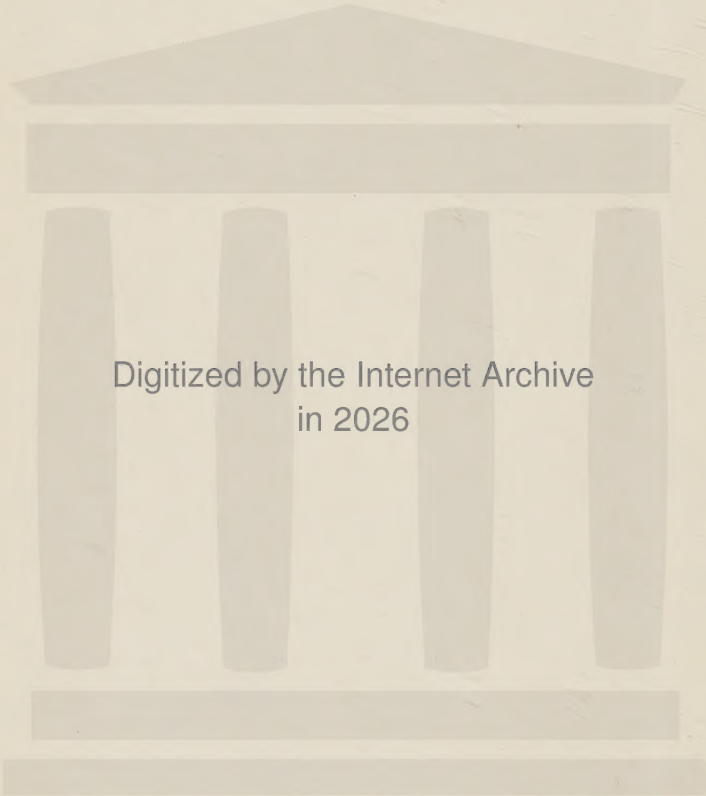
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STRUCTURE AND SURFACE

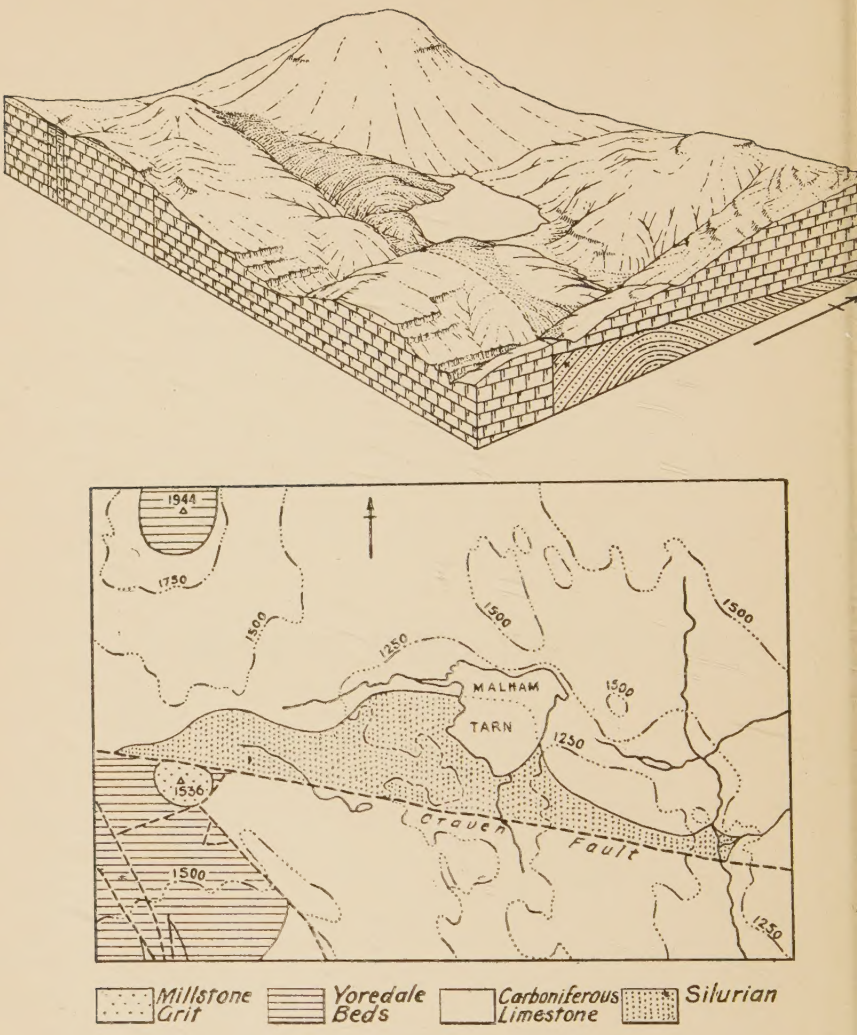

FIG. 1.—MALHAM TARN, NEAR SETTLE, YORKSHIRE.

One-inch map sheet 92 N.W., Old Series. Area shown, 9 sq. miles.

Disturbed Silurian rocks (Coniston Flags and Grits) are overlain unconformably by Carboniferous Limestone. An important fault, the Craven Fault, runs in a direction a few degrees north of west and has a downthrow on the south side of some 400 feet. Removal of overlying limestone on the north of the fault has exposed the Silurian Beds. Thus the inlier of Silurian is caused by faulting and denudation. Yoredale Beds cap the hill (Knowe Fell) in the background and occur again on the south of the Craven Fault. Black Hill, intersected by this fault, is capped by Millstone Grit.

In the block diagram the fault is shown by a broken line, the area of outcrop of the Silurian by close dotting.

[*Frontispiece.*

STRUCTURE AND SURFACE

A BOOK OF FIELD GEOLOGY

BY

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LONDON

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1929

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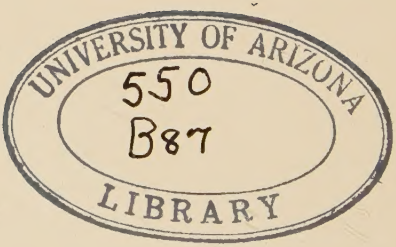

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PREFACE

THIS book is the outcome of an idea, conceived by one of the authors some years ago, of illustrating each of the simpler geological structures, first, by a general and idealized block diagram and, second, by another diagram of a tract of the Earth's surface which demonstrated the particular structure in a marked fashion. Since it was later considered that this idea of a pure sketch book would have a limited value, the plan of the book was expanded so as to embrace also the recognition of these structures in the field.

No one can doubt that the best method of the pictorial representation of geological structures, especially for demonstration to a beginner, is the Block Diagram. For, the picture representing three, instead of two dimensions as in the case of a section, it is possible to show what happens in depth: what is of even more importance to the geologist making his first essays in the field, the effects of the various structures on the surface relief can be very clearly indicated on the same diagram. Of recent years the Block Diagram has come increasingly into use for illustrating geological and geographical works, and one may predict that in the future such books will be largely illustrated, as to line diagrams, by this method.

Every diagram in this book, except parts of Fig. 97, is original, and it is believed that the idea of reproducing block diagrams from chosen rectangular areas of the One Inch Geological Survey maps has not hitherto been utilized for illustration. The pioneer in the use of the Block Diagram, it is hardly necessary to say, is W. M. Davis, and what merit these drawings may have is largely due to

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the inspiration of the published works of that master of the subject.

Our grateful thanks are due to Mr. J. Romanes, who read the manuscript and offered valuable suggestions.

C.B.B.
F.D.

CAMBRIDGE, 1929.

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STRUCTURE AND SURFACE

CHAPTER I

INTRODUCTION

THE term Geology has a very wide meaning, even if the investigation of the history of the Earth is begun at that time when oceans and the earliest sediments came into being. Geology is an observational science, being founded entirely on the basis of a countless number of facts, the knowledge of which is acquired by direct observation of nature. With the great increase of this acquired knowledge, classification of the different departments became essential, so that the Science has been split up into studies of all sorts: thus, that of the remains of organized life becomes the domain of Palæontology; that of the rocks themselves, Petrology; that of the sequence of the stratified rocks and their associated igneous rocks, Stratigraphy; and so on. Each branch becomes in time too extensive to remain a unit: thus Palæontology subdivides into Invertebrate and Vertebrate Palæontology, and Palæobotany. Further, even a single one of these divisions becomes too great for an individual to master, hence a specialist will devote his time to one form of life, such as the Echinodermata, and the science of Echinology is born.

So it can be realized that a geologist has an extremely wide field of inquiry to cover, and in a lifetime he cannot hope to acquire more than a very generalized idea of the subject matter of these divisions beyond that one to which he devotes his particular attention.

But, from beginning to end, the basis of all geological

inquiry is the observation of facts and the collection for study of material in the field. Eventually the geologist will find his work becoming more and more specialized according to his particular bent or to other circumstances, but before that specialization takes place he must learn the rudiments of the Science in the field itself.

It is with the structures he is likely to meet with in his field work and the methods of recognizing and measuring them in their inter-relation with surface features, that this book has to deal.

It is not uncommon for the beginner in Geology to imagine that the collection of material is merely the preliminary duty of the student, and that his main object is to examine these specimens in the laboratory to find out their history from their microscopic structure and their fossils. In thus spending a minimum of time in the field and a maximum in the laboratory he is putting the cart rather before the horse.

The first aim of the geologist should be to extract as much information as he possibly can from the rocks in the field and to regard the collection and more detailed work in the laboratory as a means of amplifying and confirming the field observations, but never as taking their place. Yet it is not easy for a beginner, living in a civilized and thoroughly well-mapped country, to realize this fact to the full, since his geological maps tell him at once that most of the field work has already been done for him and he naturally turns to the thrills of searching for fossils or the more purely scientific charm of the microscope and chemical analysis.

It may be said, then, that the object of his field work is to record his observations in such a way as to present a clear picture to himself and to others of what actually occurs, both on the surface and underground, in the way of rocks and rock structures. The most convenient way of recording such data is in the form of a map, so that the first object of geological field work is to produce a geological map.

The observations that he is going to make and record are therefore of two kinds. Obviously he has to make a definitely geological examination of what he sees in order to recognize and correlate the rocks, but he has also to make definite measurements of the rock masses so as to be able to plot them on his map.

The form and relief of the land will directly affect the appearance at the surface, or outcrop, of the rocks, and therefore the geologist may have to measure the surface relief of his area, that is, to make a topographical map, an operation that is not entirely geological. In fact, the geologist must know something about topographical sur-

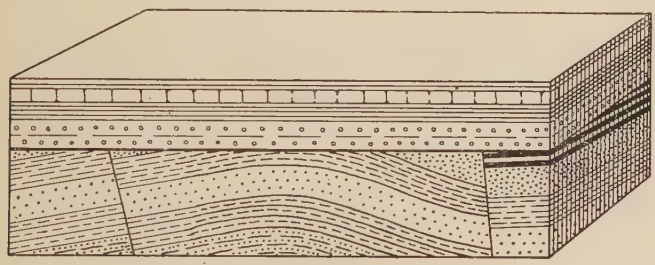


FIG. 2.—DIAGRAM OF AN UNCONFORMITY.

The older beds have been folded and faulted, planed down to a level surface, and another series of deposits has been laid down on this surface.

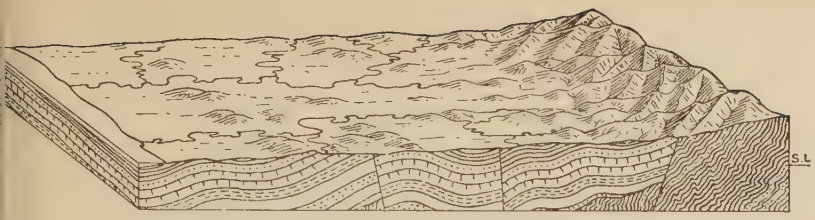
veying. The importance of this is apt to be disregarded, since most geologists are trained in a well-mapped country where detailed topographical maps can be had and the need for preliminary mapping of an area does not arise. But even in such a country the man who has some knowledge of surveying is at an immense advantage when he takes up geology, while certainly the geologist who has no knowledge of it will find, when he reaches less civilized parts of the world, that until he has made a topographical map of his district he will not be able to get very far with the geology. Moreover, it will be found that the surface features of the ground will often themselves give most suggestive evidence as to the rocks underneath and, on occasion, will be the only evidence available. For that

reason, as well as for its intrinsic interest, the study of land forms and the processes of denudation and deposition is part of the work of the geologist, who should realize from the first that every natural surface feature has a geological explanation, that is to say, is concerned with the nature and origin of the rocks which form the feature.

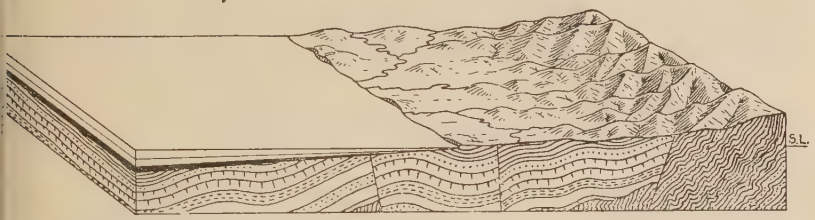
Here it seems advisable to point out the need for the young geologist to cultivate a broad vision of geological phenomena. In country such as most parts of England, where soil and vegetation cover nearly all the surface, he is reduced for exposures to the examination of a few scattered artificial openings, such as quarries and railway cuttings, to a large extent, and consequently he is inclined to view things such as unconformities as occurring over a limited area: dip and strike shown in a quarry as uniform over a large tract. He must remember that an important unconformity must be viewed as a very widespread phenomenon and must picture some such state of affairs as is seen in Fig. 3, where his quarry, if shown in the diagram to scale, would be an almost invisible speck. Likewise the dip shown in the quarry may represent merely a part of a small fold and may be quite local. It is perhaps sound advice, at the beginning of a survey of mapped or unmapped country, first of all to climb the hills and spend some time studying the details of the surrounding areas—its relief, streams, ridges, prominent and likely outcrops of rocks and the way to reach them.

To return to the subject, there are thus already added two branches of knowledge which are of assistance to the field geologist—topographical surveying and geomorphology—but it will be found that others will be called upon at times as indicators if not as direct evidence of the existence of certain types of rock. Certain types of vegetation, for instance, are characteristic of certain kinds of rock and the presence of the former may be the only indication of the latter.

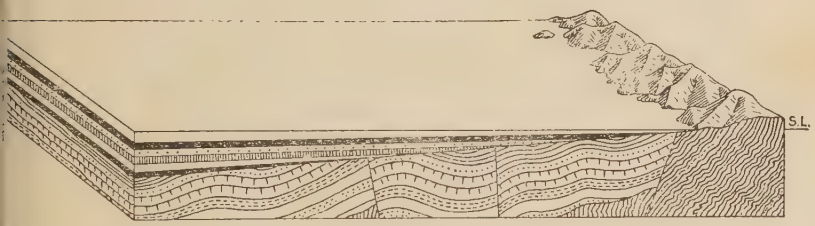
A geologist must be a skilful reader of geological maps as well as a constructor of his own, and for training in



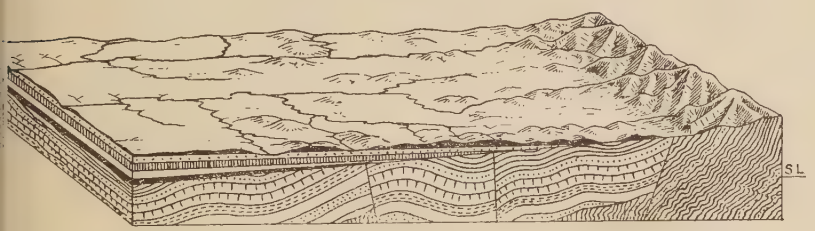
(i) An old land surface sinking: the sea advances over the coastal regions, a paneplane.



(ii) A further stage of the advance of the sea. Deposits are being laid down over a limited area.



(iii) The sea has now advanced far inland, submerging the lower mountain-slopes, forming fiords. Deposits are being laid down over a wide area, successive beds covering all previous ones and their landward margins. This is "overlap."



(iv) The land has risen again, and the sea has retired from the area. The new series of deposits is undergoing denudation.

FIG. 3.—UNCONFORMITY AND OVERLAP IN THE MAKING.

this there are several good manuals.[1] The printed geological map is naturally a finished production which should serve as an ideal for one's own. In the field coloured chalks are useful for tinting the outcrops of rock masses; but afterwards, when the finished map is prepared from the working map, water colour should be used to obtain the full effect.[2]

It is as well to adopt from the first some ordered method of representing kinds and divisions of rocks. There is no uniform standard or index sheet of conventional signs in common use, but Fig. 4 shows a reasonable set for use when it is not convenient or possible to use colour, as, for instance, in sketching or when a map or section has to be reproduced in line only. It will be noticed that the signs for any one rock are different in plan and in section. The reason is that in plan it is necessary to obscure the topographical detail as little as possible, whereas in section one may use heavier lines imitating in some conventional way the structure of the rock. These conventions will be followed in this book as far as possible.

Returning to the matter of topographical surveying, space will not allow more than a brief reference to the methods particularly suited to the needs of the geologist. Except in special circumstances the area of any particular survey will usually be small. Perhaps acquaintance with the following operations will equip a geologist reasonably well.

For the mapping of a line as distinct from an area, such as a river course for instance, or the boundary of two types of rock, a rapid and convenient method is the compass traverse. A traverse, briefly described, consists of following generally the curved line of the boundary with a series of straight lines, known as the legs of the traverse, each

[1] *The Study of Geological Maps*, G. L. Elles, Camb. Univ. Press, 1921. *Notes on Geological Map Reading*, A. Harker, W. Heffer & Sons, Cambridge, 1926. *Geological and Topographical Maps*, A. R. Dwerryhouse, Arnold, 2nd Edition, 1919.

[2] See note at the end of this chapter.

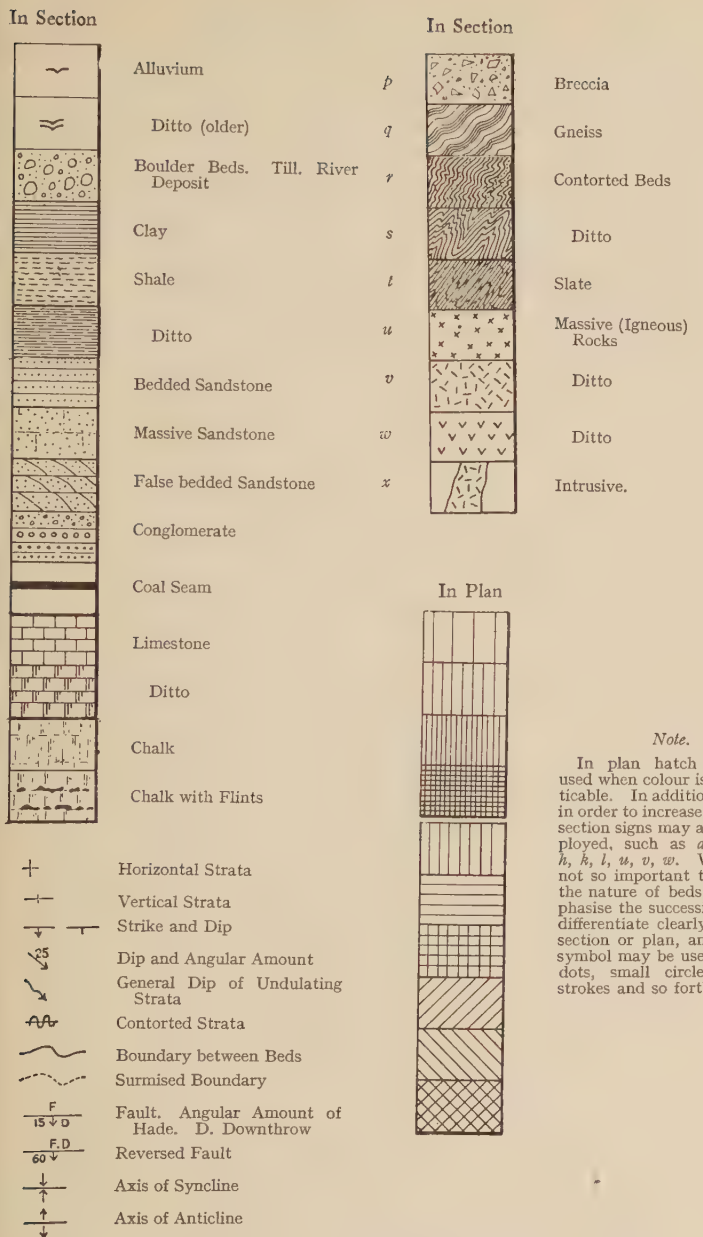


FIG. 4.—CONVENTIONAL SIGNS.

Note.

In plan hatch lines are used when colour is not practicable. In addition to these, in order to increase the range, section signs may also be employed, such as *a*, *b*, *c*, *e*, *h*, *k*, *l*, *u*, *v*, *w*. When it is not so important to indicate the nature of beds as to emphasise the succession and to differentiate clearly in either section or plan, any kind of symbol may be used, such as dots, small circles, curved strokes and so forth.

of which is measured as to distance by pacing, taping or chaining, or by tacheometry, and as to direction by taking its bearing with a prismatic compass. These straight lines are plotted with protractor and scale, thus forming a framework to which the sinuosities of the actual line can be attached, the necessary measurements having been made in the field by a series of short lines made at right angles to the legs of the traverse and at noted points in it: these lines are known as offsets. In ordinary work offsets are actually measured only if the scale of the map and the degree of accuracy required warrant it: generally it is not necessary, since sketches in one's field book serve perfectly well.

For surveys which cover an area the traverse method is not so convenient and is replaced by a graphic triangulation with the plane table, if the country is suitable for this instrument. The three most important features of this method are, that it entails a minimum of actual linear measurement on the ground, always a tedious business; that since the map is made in the field and not plotted afterwards in the office there is less likelihood of gross errors creeping in without detection: and geological details can be inserted as the map grows. The procedure in the field is rather more complicated than with the traverse method, but on the other hand the details are in themselves interesting and the results more satisfying to the worker. The plane table is a fair-weather instrument and is not suitable for thickly forested country, but in spite of these and other limitations it can be called the standard method of surveying for geological purposes. A telescopic alidade with vertical arc should be employed in preference to one with merely sighting vanes: vertical angles, and hence the elevation of points, can be determined with all the degree of accuracy that is normally required. The Abney Level has its uses: this pocket instrument will give angles to one-third of a degree of arc and, when set at zero, can be used to reveal every point in the surrounding country at the same level as the observer.

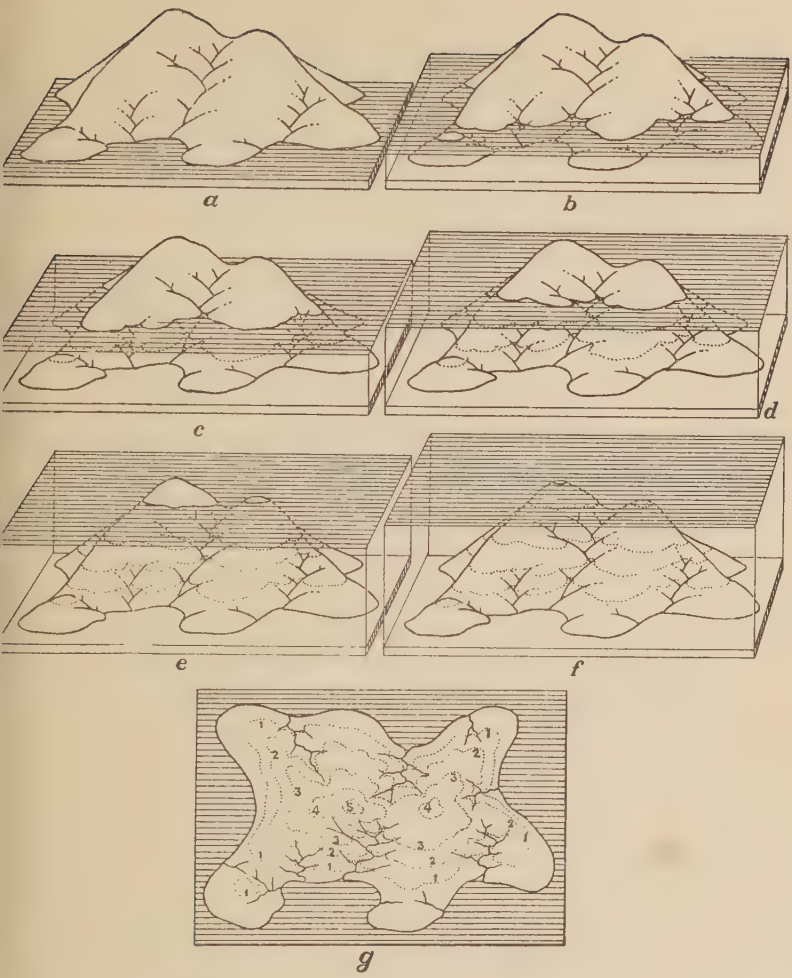


FIG. 5.—CONTOUR LINES ON A MODEL.

a. An Island. The coast line is the first contour line of zero elevation, or datum level.

b. The sea (surface shown by horizontal shading lines) has risen one unit in height, submerging the island in part. The new coast line, projected on to the basal plane on which has been drawn the first coast line, gives the second contour of elevation one unit (refer to *g*).

c, *d*, *e*, *f*. The sea has risen successively 2, 3, 4 and 5 units of height, giving rise to new coast lines, each of which is projected on to the base.

g. The projection of all the successive coasts on to the base, i.e. a contoured map of the island. Note that in *e* the peaks now form two islands, and their contours are isolated in plan; in *f* only one peak remains to give the last contour.

Facility then, in the use, of the prismatic compass and the plane table is very desirable for every geologist, and though the matter cannot be entered into in detail, some notes as to suitable types of instruments and equipment are given in Appendix I.

The cultivation of a "topographic sense," which is more than the mere ability to recognize features in the field from the map, is of great importance to the man who is always correlating such features in the field, and there is no better way of training oneself than by the constant use of a map.

This topographic sense or "sense of country" is a very real thing and implies ability in judging distance, appreciating slopes and feeling direction. This sense is usually well developed in the more primitive races and even comes naturally to some individuals of the more advanced races, but it is certainly capable of improvement by practice, especially by practice with a map. Still more rapid progress can be made if the beginner forms the habit of frequently making "form line" sketches in pencil of the country he is looking at: these are merely sketch maps with form lines added to show relief. Some emphasis may be laid on this practice, for it is often the most rapid and convenient way of making geological field notes, especially where the relative position of different specimens or rock masses is of importance. By a form line sketch is meant the roughest of plans, sketched by eye, with an indication of the relief shown by faint or broken lines which imitate contour lines in so far as they represent lines of equal level. No attempt is made to represent any particular heights or equal vertical intervals. They do, however, by their spacing indicate the kind of slope and by their plan the kind of land form of the area concerned.

Although contour lines on maps are familiar to most, their relation to the surface relief and the information they convey are not always clearly understood. In Figs. 6 and 7 the dissected block diagrams should explain without need of further mention in the text how contours show relief and supply data for measuring heights and slopes.

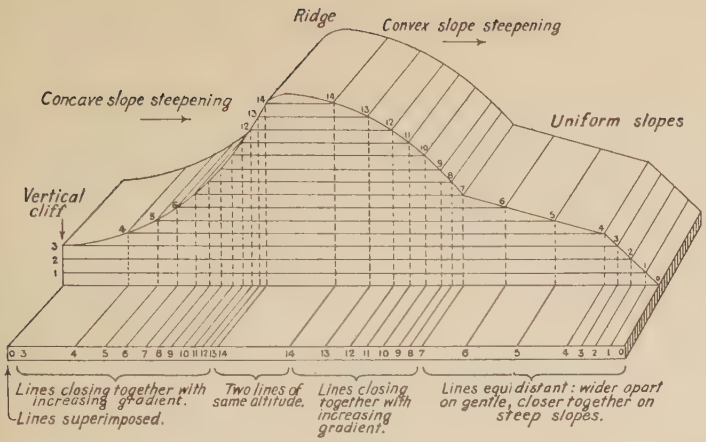

Ridge
Convex slope steepening
Concave slope steepening
Uniform slopes
Vertical cliff
Lines closing together with increasing gradient.
Lines superimposed.
Two lines of same altitude.
Lines closing together with increasing gradient.
Lines equidistant: wider apart on gentle, closer together on steep slopes.

FIG. 6.—MODEL OF TOPOGRAPHIC SURFACES.

Projection on a plane surface (i.e. a map) in the foreground shows how grouping and spacing of contour lines indicate the nature of the surface.

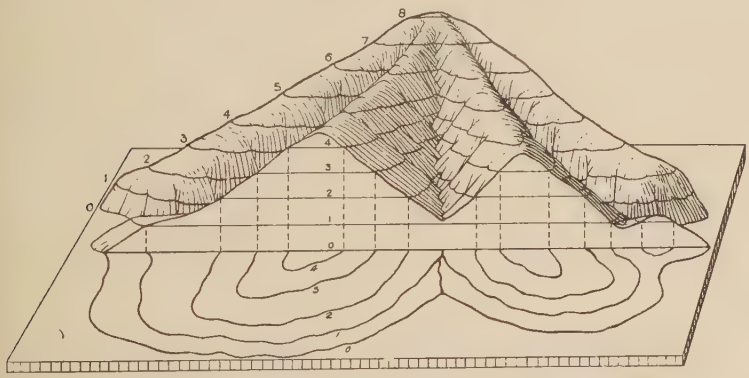


FIG. 7.—CONTOURED TOPOGRAPHICAL MODEL.

The foreground has been cut away, leaving a vertical section and profile, and showing a map of that ground. The relations of the profile to its trace (or line of section) on the map and to the solid figure are evident.

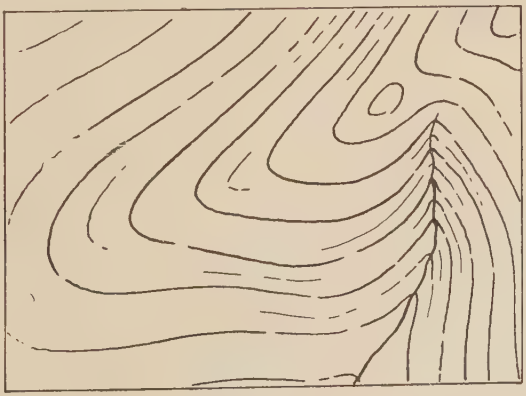


FIG. 8.—
A FORM LINE
SKETCH.

Fig. 8 shows what is meant by form line sketches, which naturally do not lend themselves to large stretches of country and are better reserved for quite small features.

In the study of geological features, whether on the map or on the ground, a difficulty arises which is not prominent in any other kind of field work: that is, the necessity of viewing things in three dimensions—of "seeing solid," as it is sometimes called. In the field, where one is dealing with natural perspective, this is not so difficult: the beginner soon learns to picture an outcrop of rock beneath the surface of a hill or to piece together the strata which are visible only in vertical section in the faces of a quarry. But when he comes to view maps and sections where features of three dimensions are represented in only two dimensions, it takes a certain amount of imagination to "see solid" and thus get a real picture of what the diagram represents. The method of showing geological features by block diagrams to some extent avoids this difficulty, and since they are the basis of all the figures in this book it will be as well to have clearly in one's mind exactly what are the characteristics and limitations of such diagrams.

The name for them is far from ideal, but it has come into such general use that it is not likely to be replaced by any more exact title such as "perspective block," though in America the term "stereogram" appears to be widely used. The essential features of the method are that a diagram shall combine in one drawing the aspects of both a plan and a section and at the same time give a perspective view of the country, lending an appearance of reality which is not readily discernible in either plan or section alone except to the very expert and practised eye.

In Fig. 9 there are four diagrams illustrating these points, comprising a contoured plan, a geological plan, a geological section and finally a block diagram drawn from these three. The piece of country is imaginary, but it illustrates a possible grouping of features.

In the contoured plan the expert eye at once picks out

the main consequent river with its subsequent tributaries coming in at right angles and flowing through gaps in two low ridges. Detailed study would show that the hills are rounded and mature near the coast, but no one could

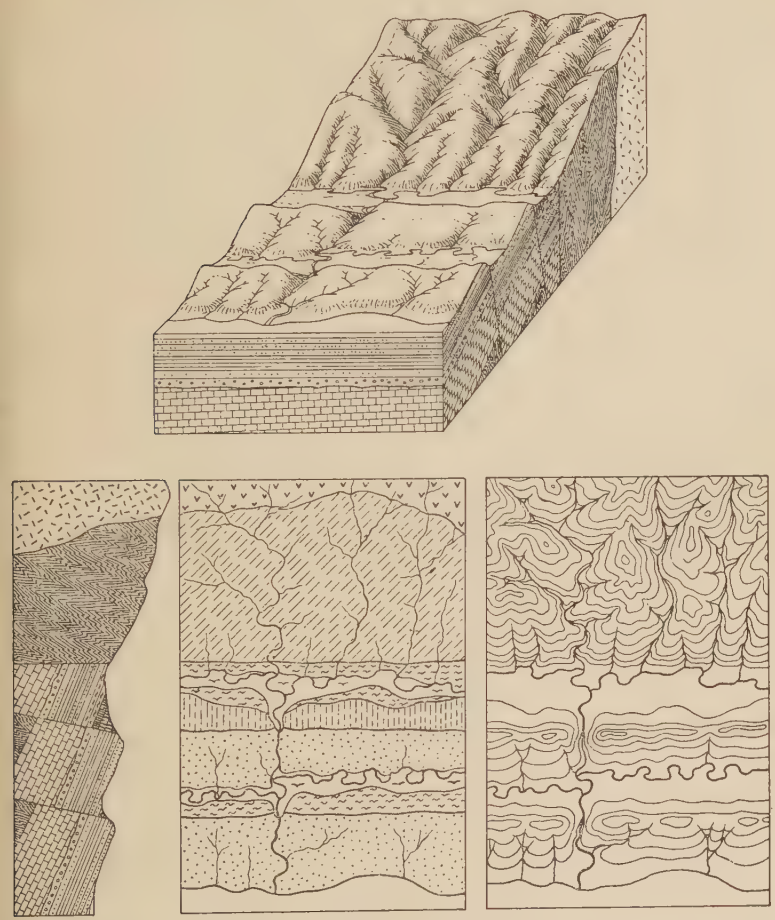


FIG. 9.—A BLOCK DIAGRAM (ABOVE). BELOW ARE A GEOLOGICAL SECTION, A GEOLOGICAL MAP, AND A TOPOGRAPHICAL MAP OF THE SAME AREA.

deduce much more than that from the plan alone. When the geological plan of the same country is consulted, however, a great deal more can be deduced about the area. The repetition of the same beds, for instance, and certain

other evidence would enable him to draw with some assurance the section shown in the third diagram. It must be noted, however, that the section does contain more information than is actually shown on the plan. Thus, the lower beds in the section do not appear at the surface nor does the unconformity between the limestone and the conglomerate, these facts being deduced from their occurrence in other parts of the same district.

It has been possible, therefore, to discover what is required from the separate study of the three figures, but it requires some practice and a good deal of careful comparison of one diagram with the other to do so at all readily. The block diagram, on the other hand, presents to some extent the aspect of all three at once, and gives a better picture of the country than any plan can give. The structure is definitely connected with the surface relief, and although the plan and the section are now both presented obliquely there is usually little lost in clearness from that source. This block diagram is in one-point perspective with but slight foreshortening from front to rear in order to render comparison more easy.

It is true that a block diagram has definite limitations: it can, for instance, represent country from one point of view only, though the angle of obliquity can be varied: further, the sections only represent those at the outer faces of the block unless one adopts the convention of dissecting the diagram, as in Fig. 29. It is true also that measurements cannot readily be made from a perspective block diagram since the scale varies from front to rear and with the direction at any one point. But in spite of these disadvantages it remains the most natural and convincing way of showing in two dimensions what really occurs in three and from the point of view of teaching rock structures is the best instrument an instructor can have.

Limitations of space prevent the insertion of the actual portion of map from which each definite geological block diagram was drawn. The reader is advised to compare the one-inch map with the diagram: the area represented

can be easily recognized from the geological outcrops and the topography.

The construction of block diagrams is dealt with in Chapters XI and XII.

Note on Colouring Maps

In using water colour for maps, each tint should be mixed just before using in a porcelain saucer in ample quantity for the whole surface to be coloured: this ensures uniformity of tint. A small quantity of colour in plenty of water should be used: dense colour should be avoided, since it is not only difficult to manipulate so as to give a smooth even wash, but it tends to obscure topographical detail and lettering. Any colours may be used, but it is better to avoid the heavier ones (such as Vermilion and Indian Red) and mixtures (such as some greens which are apt to separate out into their constituents) which always give patchy results in large washes. If it is necessary to use them, they should be applied to the smaller outcrops. Occasionally it is convenient to emphasize a particular bed, when a denser wash can be applied, such as deep Prussian Blue for thin limestones, Vermilion for dykes and igneous masses. Alluvium is either uncoloured or tinted in a very pale ochre: igneous rocks in red: limestone in blue: chalk in green.

The map should be laid on a sloping drawing board. The parts to be coloured are then washed over with clean water to damp the paper, any surplus water being removed with blotting paper. A *large* sable brush with plenty of colour should be employed, the wash being applied at the upper end of the area and brought down gradually with an advancing horizontal "front" of liquid and ended off in one corner, any excess of wash being picked up with the point of a clean damp brush.

CHAPTER II

THE GENERAL FORM OF ROCK MASSES

SINCE textbooks of Geology treat fully of the origin of rock masses and their forms, only brief reference need be made to the subject before one passes to the detailed structure of rocks which is the study of the geologist in the field.

All rocks are classified, according to their mode of origin, as far as possible into two divisions, representing, on the one hand, those which can be called original, having solidified from a molten magma, and, on the other, those which have been derived from the former by the familiar processes of erosion and deposition. But old rocks of either division may have been so changed by heat and pressure that it is difficult to refer them to their original class, so a sub-division for these is usual and the whole scheme may be represented as follows:

Original or Igneous Division	Derived or Sedimentary Division
Granites, dolerites, lavas, etc.	Limestones, sandstones, shales, etc.

Altered or Metamorphic Sub-Division
Gneisses, schists, slates, etc.

There are some other rocks, such as ores, which do not fall naturally into either division, but these are comparatively unimportant from the present point of view. One must be prepared to find the rocks of one division simulating those of another, as when a volcanic lava is laid down

in a thin bed like a sedimentary rock, but on the whole the divisions are fairly distinct both in outward appearance and internal structure.

It is the object of the geologist to be able to classify with more or less precision any rocks he meets with in the field, and this he does by a series of observations. The general form of the rock mass, the composition and grain structure of the rock itself, its inclusions whether of fossils or portions of older rocks, all tell him something of its history; but of all these the first must, if possible, be considered before attention is given to the others, since it usually holds the key to its origin.

It is obvious that the surface of all rock masses is undergoing a steady degradation by erosion, the products of which are always laid down at a lower level and the greater part of them below the sea. If this process were to go on quite unchecked the land masses would ultimately all be reduced to shoals below sea level. It is not so obvious to the casual observer that there are at the same time counterbalancing processes going on in the form of eruptions and intrusions of igneous rocks, and of folding and elevation of existing surface rocks, both tending on the whole to counteract the other process and erect new land masses as fast as the old ones are eroded. The study of the balance of these two processes in the past is, in fact, the basis of Geology and the latter is the subject of the special branch of geology known as Tectonic Geology.

It can therefore be said that the picture in Fig. 10 is typical of the world at present and also far back in geological time. The mountainous interior, undergoing the maximum of the erosion process, the highlands or plateau of more rounded forms dissected by rivers, the low coastal plain where erosion is more moderate and where there is even a certain amount of deposition going on, can all be recognized in most parts of the world. The products of these reducing forces are ultimately all laid down at and below the sea level on the more or less level platform which in most parts of the world forms a "continental

shelf." The shelf begins to slope more steeply at about 100 fathoms below sea level to form the "continental slope" which dips down to the more abyssal depths of the ocean where very few of the products of land erosion are found, so that there is nothing but a vast plain of the finest coloured ooze formed by the skeletal remains of marine plants and animals and by volcanic dust.

The section at the side of the block diagram gives a somewhat generalized picture of the former geological history of the area which is easily interpreted. The foundations of the whole block consist of much contorted metamorphic rock which may have been originally either

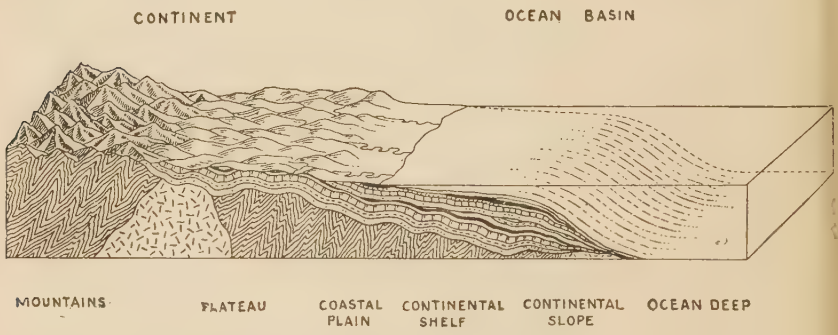


FIG. 10.—TOPOGRAPHICAL FORMS.

igneous or sedimentary. These foundations were invaded by at least one formless mass of igneous rock before the first recognizable sedimentary rocks were laid down. The earliest of these is a conglomerate, as would be expected with erosion starting on a new area of uplift; then comes a sandstone grading probably into a finer grained shale and then into a massive limestone. The whole series tells of a gradually increasing depth of the primeval sea in which they were formed, for the limestone is made up almost entirely of the skeletons of marine animals undiluted by muds from the land. Coal beds follow, which denote an uplift to a height at or above sea level again; they have been denuded in places, which shows a later uplift long after they had been laid down and con-

solidated. Another subsidence then took place and more marine deposits were laid down upon the older ones: they are unconformable and the unconformity marks a period of pause in deposition. These uplifts and subsidences naturally involve compression and earth movements, so that the older rocks are folded and contorted more than the younger, although, as has been seen, all the beds of materials must have been originally laid down in nearly horizontal layers. One further fact of importance emerges from the diagram, and that is, that although the higher mountains are now formed of the oldest rocks, they may have been, and probably were, formerly covered by some of the marine deposits.

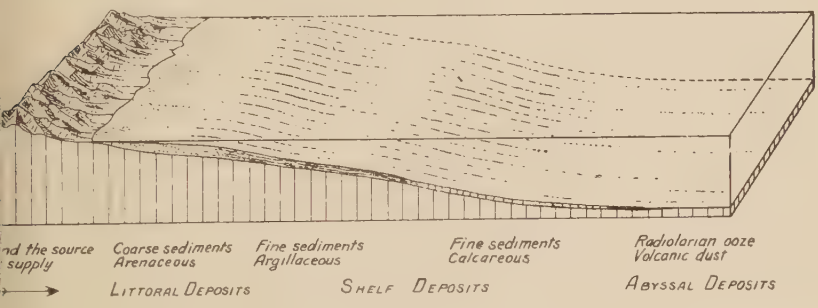


Fig. 11.—Lateral Variation.

Such a generalized diagram is to some extent misleading by its very simplicity, but it does represent the actual facts of the two processes of erosion and deposition, and it illustrates how the evidence presented by a series of beds may be made to yield the main facts in the former history of the area.

But so far it has appeared that there are marked differences of type between successive beds, as though the conditions for any one layer were of great duration and held good over a large area. This is not always the case: moreover there sometimes occur fresh-water deposits which are even more likely to be local and to thin out in certain directions or change to a totally different kind of rock.

Fig. 11 represents a section, on a much smaller scale

than Fig. 10, from the highlands of a continent out to the ocean deeps, possibly many hundreds of miles from the shore, and clearly a change must be expected in the character of the deposit further and further from the land. Thus the foreshore deposits will be coarse gravels and shingles which sink to the bottom first and which, when consolidated by time, will be called conglomerates or grits. Next in procession from the shore are found sands, later in time to become sandstones, while still further out only the finer particles of mud brought down by the rivers will penetrate and will consolidate to shales. Mixed with all these will be the hard parts of all the marine animals which lived at the time, but these will not form a large proportion of the total deposit until at a distance so far from the land that but little of the mud reaches it, when there will be a mixture of marine remains (composed chiefly of lime) with clayey materials forming anything from a marl to a chalk or limestone. The important things to realize are, first, all these deposits are contemporaneous and not successive, and second, that the deposits will, on the whole, accumulate more rapidly near the coast than further out. From these facts one arrives at a fundamental deduction, not always fully appreciated, that the kind of rock, limestone, sandstone, shale and so on, does not of itself give much indication of its age, although it gives comparatively full indication of the circumstances in which it was laid down. Nor does the hardness of the rock necessarily indicate age, for there are soft clays in Russia of Palæozoic age and hard sandstones of Tertiary age in England.

It has been mentioned above that lateral variation is to be expected in deposits laid down over a considerable section of sea floor, but it is obvious that the same thing happens on a miniature scale over smaller areas of deposition, especially in estuaries and lakes. It is indeed rather remarkable that so many strata are comparatively uniform in character over wide areas, but this occurrence must not be assumed to be universally true. From the foregoing it is clear that of the three types of deposit, shingles, sands

and muds, the latter are the most likely to be widespread, and the former the least likely. When, however, a coast line is slowly sinking, the area covered by the coastal belt of shingles and sands is increased, and this, in fact, is the reason for the great extension of some conglomerates and sandstones. It should be noted that in such a case the various sections of similar character in a horizontal direction are not strictly contemporaneous.

In such cases as estuarine and lake deposits where the lateral variation is local in character one must be prepared to find various minor structures in any one series of beds which at first sight are liable to be very confusing to the field geologist. When, for instance, there is frequent re-arrangement of the particles of sand or when a sand-bank is built outwards by successive layers transported to where the bottom shelves rapidly to deeper and calmer water, the formation known as false or current bedding arises. This is often associated with lenticular bedding in which a coarser bed appears lens-shaped in section. Under such conditions also there may be contemporary erosion, that is to say, the cutting away of part of a deposit soon after it has been laid down. The most striking case of this is found in coal-fields in England and elsewhere, in which a coal seam may suddenly end in sandstone and shale, a stream having eroded the seam and subsequently infilled its channel with its deposits.

In deposits which are partly due to the action of water and partly to other agencies, such as wind or vulcanicity, these structures may be extremely complicated and difficult to follow. They are, however, of comparatively minor importance and are dealt with in detail in text-books of general geology. Mention is made of them here in order to impress upon the student the importance of even the miniature variations of structure in a rock, each of which has its interpretation. Take, for instance, the case of a lake which had its supply of water from snow-covered mountains. The summer melting of the snow causing annual floods would deposit each year a fresh layer of mud

in the deeper parts of the lake. When in future ages the mud had consolidated to a finely laminated shale each lamina would represent the lapse of a year, and a count of the laminæ would give an approximation to the length of time taken for the formation of the whole deposit.

To return again to the typical forms of rock masses, it is clear that since the Igneous rocks are for the most part intruded from below into the surface rocks regular forms cannot be expected. Such types as are met with are treated separately in Chapter VII. The metamorphic group may also have somewhat irregular forms, and what original structure they may have had may be quite lost owing to the excessive contortions of the strata or may be masked by a superimposed structure due to pressure, known as cleavage.

On account of their massive character neither the Metamorphic nor the Igneous rocks are likely to affect the surface form of the land where they outcrop in any regular or typical way. It may be said generally that massive igneous rocks tend to give rounded forms to mountains and that metamorphic rocks tend to give sharper forms, but neither assertion can have the force of a rule.

With sedimentary rocks, however, the case is quite different, and it is upon the regularity of the forms of these rocks that the work of the geologist in the field largely depends. Thus, when a comparatively thin bed of hard volcanic rock is found outcropping at the surface as a dyke, little can be said about its size and shape below ground except that it comes from some parent magma. On the other hand, in the case of a well-defined bed of sandstone outcropping at the surface, its continuance in much the same proportions below ground can confidently be expected, and measurements of its dip and strike can be made in order to find out where to look for its continuation in another place: it represents a considerable period of time during which it was laid down under conditions not different in any essential respect from those of the present day. It was the result, in fact, of a long process and not due to a

single catastrophic incident as in the case of a volcanic dyke.

It is therefore not surprising that the chief subject of the geologist's field work is the Sedimentary series, and it is chiefly with the general form and structure of these that he is concerned.

Fig. 12 is a simple representation of the chief forms of rock masses. The sedimentaries, resting on the contorted and comparatively formless metamorphic rocks as well as on the massive igneous rock, represent a phase of continuous deposition. That is to say, there are no unconformities,

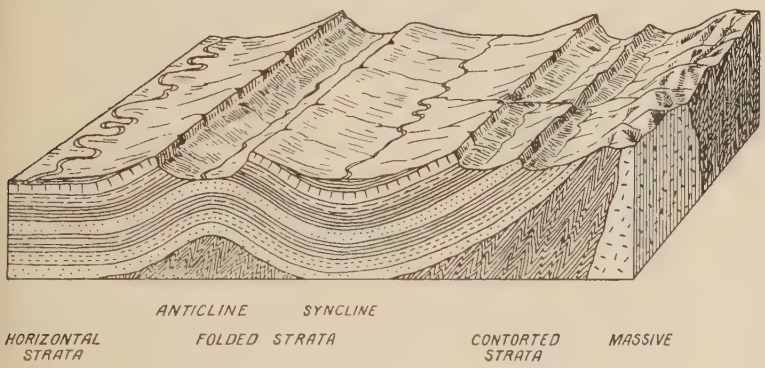


Fig. 12.—Forms of Rock Masses.

and the succession from conglomerate at the base through shales and sandstones to limestone can be interpreted as due to deposition on a sea floor which altered at times in depth but never became dry land and subject to erosion. The strata have later been laterally compressed into the simplest kind of fold, forming a single crest and trough known as an anticline and syncline. It is upon such folding that the geologist depends for his knowledge of what beds lie beneath the immediate surface at any point, for in this case if the eroded ends of the strata did not appear at the surface near the mountains he would be entirely ignorant of the existence of the lower half of the series. Such strata as these naturally differ in physical characteristics, such as porosity, density, solubility, grain

size, and alteration they have undergone since they were laid down. For the moment these variations are of importance only so far as they render the strata susceptible of denudation, but as the diagram shows they have a profound effect on the surface relief. Further reference will be made to the interdependence between surface and structure, but it is important for the student of field geology to realize that the type of relief shown in the diagram is not only real but inevitable, and that as a geologist he will receive the greatest assistance in the field from a study of the land forms which furnish to some extent an index to the rocks composing them, just as the geomorphologist

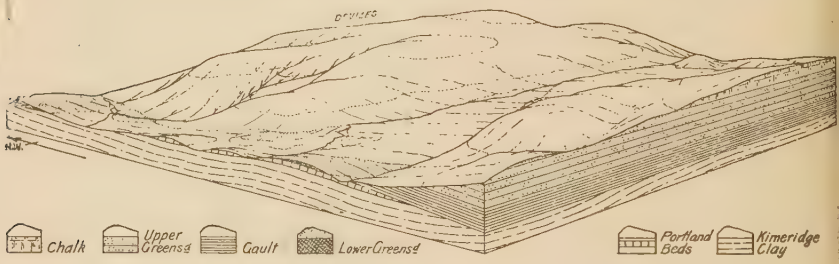


FIG. 13.—PART OF THE VALE OF PEWSEY, SOUTH OF DEVIZES, WILTS.
Sheet 282 N.S. Area shown, 14½ sq. miles.

Lower Chalk, Upper Greensand and Gault overlap Lower Greensand, resting on the last named and on a denuded surface of Jurassic Beds (Portland and Kimeridge). The Lower Greensand is shown stippled. Note the unconformity between the Lower Greensand and the Jurassic. The sections do not actually show the overlap of the Gault.

or student of land forms must rely on his knowledge of geology to help in the interpretation of the relief.

In this diagram (Fig. 12) the simplest type of folding and a single series of strata are shown. Such simple areas do occur in nature, but they are comparatively rare. What is much more common is the state of affairs represented in Fig. 54, where there are more complicated sets of folding, actual fractures of blocks of land known as faults, and more than one series of deposits. Even that figure is simpler than is commonly found over such a large area as is there represented, and in general it will be found that the diagrams in this book are simplified,

minor complications of structure being ignored for the sake of clearness. Fig. 3 is a good example of still another form of sedimentation known as "overlap," which must always occur when the sea transgresses the land surface as shown. Study will show that there is another instance of overlap in the same diagram in the older folded strata. Fig. 13 shows the well-known overlap of the Gault in the Vale of Pewsey, Wiltshire.

The ideas contained in the expressions overlap and unconformity are sometimes likely to be confused. When a land surface, of older rocks which have been planed down by denudation, is submerged and a new series of sediments is laid down upon it, the junction of the older rocks and the newer beds is an unconformity. The sea advances slowly over the sinking land surface and each bed that it lays down will cover a larger area landwards than the previously deposited bed. These successive beds thus overlap and give rise to unconformity with overlap. If an unconformity is examined over only a small area, there may be no signs of overlap, but somewhere else they will be found unless the unconformity is lost sight of on account of burial under more recent deposits or because of the effects of earth movements.

CHAPTER III

MEASUREMENTS IN THE FIELD

IT has already been pointed out that the geologist's field observations should all lead up to the construction of a geological map of the area which he is investigating, and to do this he must be conversant with the methods of making and recording certain measurements. In this chapter it will be assumed that only sedimentary rocks are being dealt with, since, if the principles as applied to them are thoroughly mastered, no difficulty will be found in applying these principles to the study of the outcrops of igneous rocks as dealt with in Chapter VII.

Before dealing with actual field methods it is essential to get a clear conception of a few simple ideas and definitions. It has been shown that the majority of sediments are laid down upon an approximately horizontal floor and therefore begin their existence as a sequence of horizontally bedded strata. Were earth movements restricted to mere elevation and depression these beds would remain horizontal and, after elevation, the only exposures of earlier rocks would be found on the sides and floors of valleys and in cliffs. In most cases the thickness of beds thus exposed would be relatively small, so that the knowledge to be gleaned of the history of the Earth in such an area would be meagre indeed.

In such circumstances the geologist's work of mapping the distribution of rocks would become so simplified as to be monotonous. The strata would, in fact, outcrop along contour lines, while the thickness of any one bed would be simply the difference in elevation between the top and bottom of the bed. Fig. 14 should make this clear.

Earth movements are, however, much more frequently of a compressional kind leading to the folding of the horizontal strata: as soon as these folds emerge from below sea-level they are attacked by the agents of erosion so that in course of time, in an area of intense folding, beds of very different ages may all be exposed at the surface within a comparatively small area. Even when the movement is mainly one of elevation it is rarely of equal amount over a wide area, so that in general warping and tilting of the beds again gives denudation the chance of exposing a variety of beds at the surface, though in such a case a less range will be seen in a given area. Strictly horizontal beds are therefore the exception and consideration of them will be deferred to a later part of this chapter.

Wherever non-horizontal beds are under consideration two highly important measurements become essential: these are *strike* and *dip*. A study of Fig. 15 (p. 31) should make the meaning of these two terms clear. If it be remembered that the dip is the greatest gradient down the bed and that the strike is the direction of a horizontal line on the bed at right angles to this, no difficulties should be encountered.

To record dip, two measurements are necessary: (*a*) the direction and (*b*) the angle measured from the horizontal. In the case of strike the only measurement is that of direction, and this is always at right angles to the dip: for example, if a bed dips to N. 45° W., it must strike at N. 45° E. irrespective of the amount of the dip. It should, however, be noted that for any given strike two directions of dip are possible, these being opposite to one another: for example, if a bed strike N.–S. it may dip either east or west. Fig. 15 also illustrates another point to be remembered when dealing with dipping instead of horizontal beds; that is, that the true thickness is no longer the difference in height between a point on the top of the bed and a point vertically below on the base, but must be measured in a direction at right angles to the plane of the bed.

It has probably been realized what is meant by outcrop,

but a definition may be given here. Outcrop is the area of the surface of the ground occupied by a bed, and its form will depend on three factors—the thickness of the bed, the direction and amount of dip and the topography of the land surface. Thus a thin horizontal bed occupying the surface of a level plain would have an outcrop of very wide extent: the same bed dipping steeply and uniformly would be represented by a straight narrow belt across the plain.

It is essential for the field geologist to accustom himself to regarding such an outcrop as the intersection of two surfaces either of which may be regular or irregular. The one is the surface of the ground, the other that of the bed; where the former is higher than the latter, the surface of the bed is hidden below ground: where the converse is the case the surface of the bed is non-existent—that is to say, it has been eroded away. Once this conception of outcrop is clearly visualized in the solid it is comparatively easy to extend the solid picture to the case of the outcrop of a bed of definite thickness.

The construction and interpretation of a geological map is thus in many respects a problem of solid geometry. This subject, however, belongs more properly to Chapter IV, where it is fully dealt with.

Turning now to the practical problem of constructing a geological map it will be realized that if the geologist is provided with or has prepared a detailed contoured map of the area in question and is able to plot on it with accuracy the junctions of the various beds, he will be in a position to determine from the resulting map not only the dip, strike and thickness of the beds, but their geological structure. Conversely, with a sufficiency of accurate measurements of dip and strike at various points the complete outcrop can be plotted on the contoured map. In nature, however, outcrops are rarely so continuous or so good as to fulfil either of these theoretical considerations, so that geological mapping must in most cases be a compromise between the two, and where outcrops are numerous

the two methods form a useful check on each other. The geologist in the field should never ignore any chance of direct observation so that wherever possible he has a cross check on his measurements.

It will be convenient first to consider the tracing of a particular bed along its outcrop, and then the actual field measurements where a bed is well exposed at the surface, although in practice these two operations would be carried out more or less simultaneously.

The cliffs of a bold seashore present a good geological section for the beginner to practise upon: one may commence with a cliff section of horizontally bedded rocks such as is represented in Fig. 14, provided it is remembered that such an example is exceptional. If, further, it is supposed that the strata are of sandstones and shales alternately, a quite common occurrence, some features can be observed which will be a guide when search is made for a given bed away from the cliffs where it is less evident to the eye.

To begin with, one notes that the effect of weathering is not the same on the two kinds of strata, the more friable rock showing gentler ground slopes than the more consolidated and cemented. Normally it will be the sandstone which gives the steeper slope, but this is not universal: the resistance to weathering depending not so much on the grain size of the particles as on the nature of the cementing material and even on the kind of weathering the rock undergoes. Differential weathering is usually much more apparent on bare cliffs than on slopes covered with vegetation, but the keen eye will often detect characteristic differences even under such conditions, especially if the strata are sharply contrasted, as, for instance, between clay and chalk.

The permeability of the beds by water, besides affecting the rate of weathering, may be a direct guide to boundary lines between strata. If the sandstone, for instance, is porous and the shales are comparatively impermeable, the junction of the two upon a hill-side will be marked by

a change in luxuriance of the vegetation or even by a line of springs. The Chalk of England and France is a good example, and in many places the base of the Chalk is indicated by the siting of villages and houses which are placed where the water, which has passed easily through the Chalk, is held up by the less permeable strata below it.

Many other indications of the outcrop will occur to the observant student. Where the outcrop is wide it will be characterized by certain types of soil and subsoil, and this in turn means that there will be differences in the vegetation.

Certain plants are typical of limestone outcrops, others are only to be found where sandstones are giving rise to

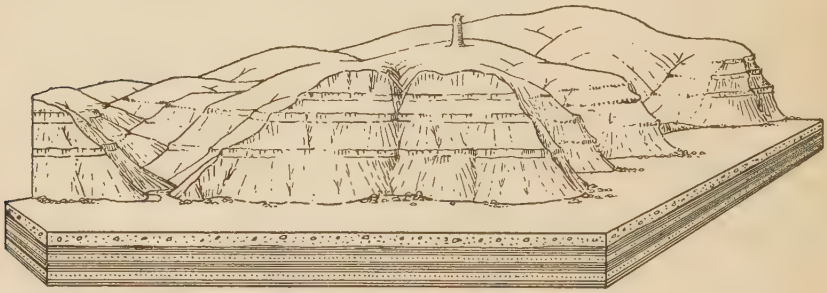


FIG. 14.—HORIZONTAL BEDS ON A COAST.

a sandy soil, and so on. A point not to be overlooked, however, is the possibility of lateral variation, which means that traced along the outcrop a sandstone may gradually merge into a shale, or a shale into a limestone. In such a section as shown in Fig. 14, if the cliffs are of considerable extent it will usually be possible to find a certain amount of lateral variation in some of the beds and in the coarser-grained ones to note possibly such features as current bedding and lenticularity. Having searched for and studied such small points of evidence one has now to record these observations and make certain measurements.

Considering now the actual measurement of dip and strike, a case such as that illustrated in Fig. 15 will first be considered. Here no great difficulties will be encountered in making the required measurements. In an

exposure of this nature it is generally fairly easy to estimate the direction of strike and to take a bearing of this direction with the compass. In many cases this can be done by eye, but in taking a bearing of such a direction it is better to stand away from the points giving the direction, if necessary putting in sticks to mark it clearly, or laying a stick horizontally along the bed, and then selecting some distant object in line with these points, the bearing being taken to this distant object.

When the direction of strike has been measured, since this is generally more easily determined than that of dip, the

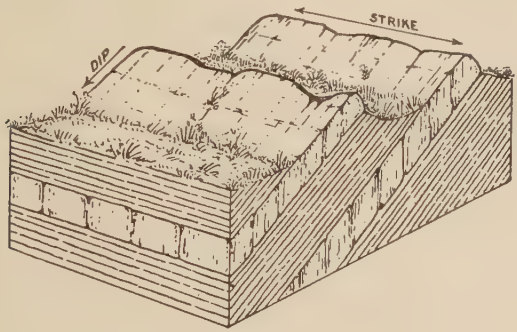


Fig. 15.—Dip and Strike.

latter is taken at right angles to the strike direction and the angle of slope is measured by the clinometer.

In doing this care must be observed in getting the true slope. If a clinometer with a base of only two or three inches is placed on a somewhat irregular dip slope, it will be realized that a very false reading may be obtained owing to these irregularities.

Simple as these measurements of dip and strike appear, the student in the field will soon find that cases occur which present considerable difficulties. If, for example, he finds a hard bed such as a sandstone or limestone giving a well-defined outcrop diagonally up sloping ground, he is apt to jump to the conclusion that a bearing along this well-defined outcrop will give him the strike of the bed. Clearly this is not so, except in the case of a vertical bed,

since the line of outcrop is not horizontal. In such circumstances it is often a difficult matter to estimate the true strike, and it may be necessary to examine the bed closely and to excavate its surface so that the direction of dip may be obtained and from that the direction of strike. A similar difficulty may be met with in the measurement of dip if the only exposures met with are sections through the beds.

If a drawing-board is inclined at an angle of, say, 10° on a table, its dip can be measured by a clinometer placed on its surface in the direction of its steepest slope. Put in some other direction, it gives a smaller reading than 10°, the angle decreasing with its divergence from the direction of the steepest slope, until, when the clinometer is at right angles to that direction, that is to say is lying along the strike of the board, the inclination will be nil.

Since the angle of inclination of the bed thus depends upon the direction in which it is measured and varies from nothing in the direction of strike to a maximum in the direction of the steepest slope, it is necessary to specify the latter as the *true dip*, all others being known as *apparent dips*. For a diagrammatic representation of this see Figs. 16 and 17.

In a cliff face, for instance, the inclination of the beds will only be the true dip if the face of the cliff is running in the direction of the steepest slope of the beds, and, in fact, the inclined strata may be very misleading even to the simulation of a fold, as shown in Fig. 16. Obviously, from one apparent dip nothing can be calculated, but if two apparent dips in different directions can be measured then the amount and direction of true dip and therefore the direction of strike can be calculated. This problem has received some prominence in books on field geology, trigonometrical and graphic solutions having been given by Green, Jukes-Brown, Harker and others. Actually the problem rarely becomes a practical one except in quarries and mines and, in general, over small areas, because over large areas strata are rarely found with a constant dip.

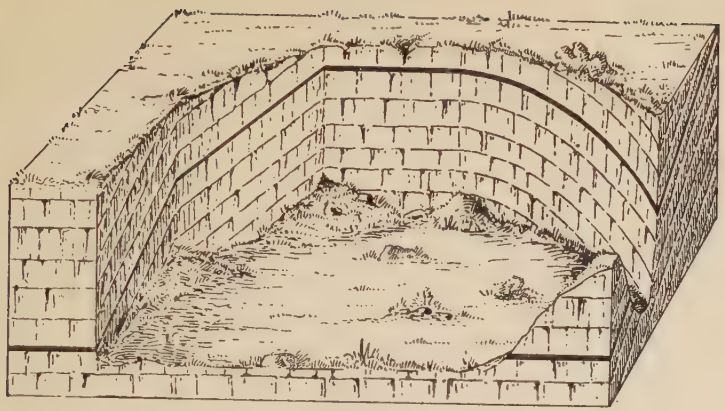


FIG. 16.—DIPS AS SEEN IN A QUARRY.

Sketch showing how strata may give any apparent dip from nil to the maximum or true dip, according to the disposition of the quarry face with regard to the direction of strike of the strata. On the curved face on the right the continuously increasing apparent dip gives the effect of a fold.

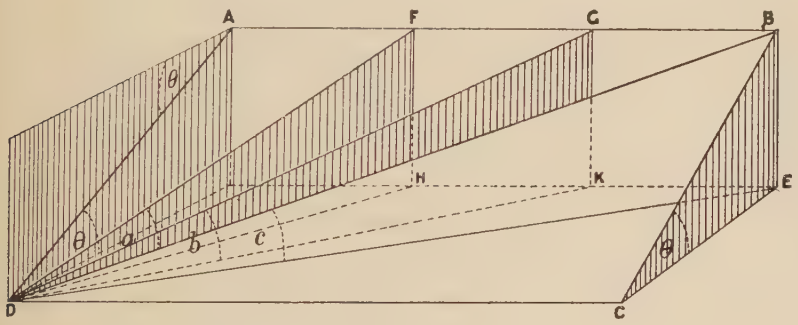


FIG. 17.—GEOMETRICAL DIAGRAM OF A DIP.

The plane ABCD represents a stratum inclined at an angle θ to the horizontal plane DCE. Any straight line in this plane drawn parallel to the horizon, as AB, DC, gives the direction of strike: any straight line drawn at right angles to the strike, as AD, BC, gives the direction of dip, and amount θ. Straight lines drawn in the plane in any other directions as DF, DG, DB, make angles with the horizontal plane, *a*, *b*, *c*, apparent dips which must be less than θ. (For while the intercepts FH, GK, BE, remain equal, the hypotenuses and bases of the triangles are greater than CB and CE.) In the diagram the lines FD, GD, BD are successively more divergent from the true dip BC, making the apparent angles of dip *a*, *b*, *c*, smaller and smaller. Eventually, by increasing the divergence sufficiently, a line could be drawn from D indistinguishable from DC: then the angle of dip will be nil, and the line coincides with the strike. Hence in a section along the strike, an inclined stratum appears to have no dip.

In nearly all cases an energetic use of the hammer on such exposures will enable at least a close approximation to true dip to be made. There are occasions, however, when it may be necessary to obtain true dip from two apparent dips. The simplest graphical solution is as follows. Having measured two apparent dips in different directions, convert the angles to gradients: that is 1 in 6, 1 in 2, as the case may be.[1] The procedure is then as shown in Fig. 18. From a point A draw AB along the bearing of one apparent dip, the length of AB being equal to the horizontal equivalent of the gradient. Draw AC similarly for the other apparent dip and join CB. From A draw AD perpendicular to CB: then AD gives the direction and amount of true dip. This graphical method is also useful in section drawing where the line of section may not coincide with the true dip of a series of beds and the appropriate apparent dip must be obtained. In this case draw a line CB (Fig. 20) along the direction of strike: draw a line DA perpendicular to it and equal to the horizontal equivalent of the gradient of true dip. Through A draw AE along the required direction of the section: then the required apparent dip will be given by AE.

Other solutions to this problem are given in Appendix II.

In general the determination of dip and strike are most easily made when the dip is considerable, say 15° or more. In many practical problems the importance of accurate measurement of dip and strike is greater where the dips are low, so that although horizontal and low dipping beds present the simplest geological structures they give rise

[1] By gradient is meant the tangent of the angle of dip, that is to say, the ratio of the vertical fall to the horizontal distance. The vertical fall is taken as unity and the horizontal distance, usually called the horizontal equivalent, is expressed in the same units. Thus in Fig. 19 the gradient of the slope A'B is $\tan \theta$, or $\frac{A'A}{A\,B}$, or $\frac{1}{2}$. Some clinometers give direct readings of the tangents of vertical angles: failing this, a simple construction on squared paper with a protractor will give a close approximation to the required horizontal equivalent.

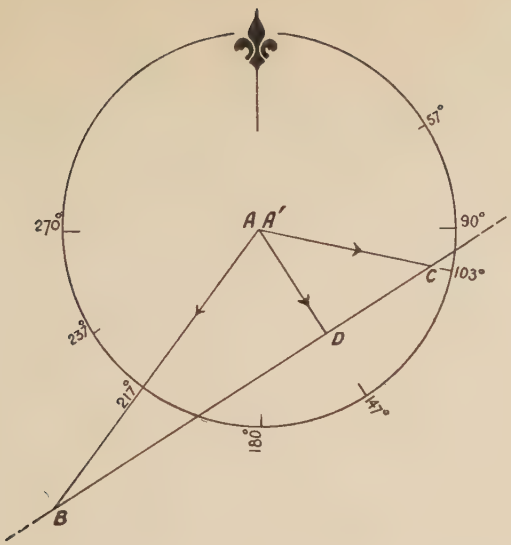


FIG. 18.—A GRAPHICAL SOLUTION OF THE APPARENT DIP PROBLEM.

The bearings of the two apparent dips AB, AC, are plotted. AB is made equal to $\frac{1}{\tan\theta}$ in any units, where θ is the angle of apparent dip. Similarly AC is drawn equal to $\frac{1}{\tan\varphi}$ in the same units. Then AD, perpendicular to BC, is the direction of dip and its slope is given by tan (angle of slope) $= \frac{1}{AD}$.

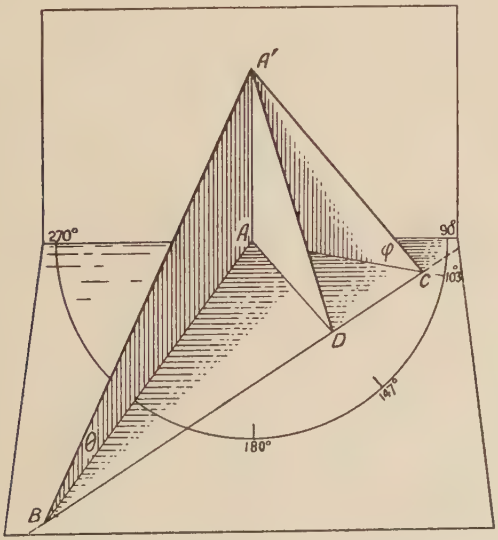


FIG. 19.—A PICTORIAL VIEW OF THE PLAN SHOWN IN FIG. 18.

Note that a vertical plane has been introduced to serve as a background.

to much more difficult problems where accurate measurements are required.

Referring back to Fig. 14, it was presumed that the beds are horizontal, but it must be ascertained that they are so, for a slope of, for example, 1° in the direction of the cliff face would not be apparent to the eye on a short length of cliff, yet if followed for three miles would have sunk any particular bed nearly 300 feet, that is, below the level of the sea. The beginner will at once think of his clinometer and selecting a part of the cliff face where he can rest it on a definite and smooth bedding plane will observe the angle; or, standing at a distance away from the

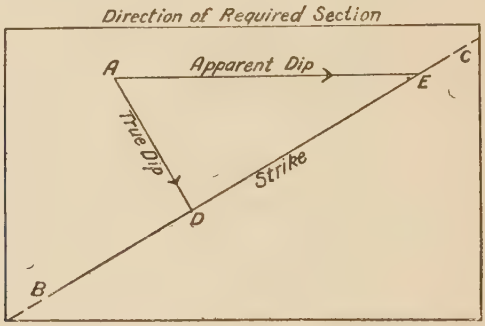


Fig. 20.—To Find the Apparent Dip in a required Direction.

cliff, will hold the base of the clinometer at arm's length and parallel to a well-marked bed. There are cases when nothing else can be done, but this is not the best way of determining a *slight* dip. To begin with, it is not always that a trustworthy bedding plane is exposed, and even so it must be remembered that although the strata are horizontal on the average there will be places where the bedding planes will be slightly inclined. Further, the ordinary type of pendulum clinometer is hardly to be trusted to a single degree, nor is it intended for such refined measurements.

There is a much more accurate method to hand: that is, to observe the height above sea level of any particular well-marked band of rock at either end of the cliff. This can

be done either by direct vertical measurements, where that is possible, or by the indirect method given below. With an Abney Level, an instrument which is capable of readings accurate to a third of a degree, a simpler method still would be to climb up to the marked bed and sight to a point in it as far along the face of the cliff as possible. Naturally if, as in the diagram, the beds are visible on one headland after another along the coast there will be no need of measurement, since even a small dip will be apparent over such a distance.

The observation is, however, not yet complete, for so far it has been determined that the beds are level in one direction only, that is along their exposure on the sea cliff: one must make sure that they are level in the direction at right angles before it can be said they are truly horizontal.

If the cliffs are interrupted by valleys a sight may be taken up one of them to an exposure where the selected bed can be identified, or one may even have to go inland to identify it and find its height by estimation from the nearest Survey Bench-mark or by other more tedious ways hardly worth the trouble. When one is satisfied that the strata are level bedded over the area concerned, the plotting of their boundaries on a topographical map will be simple since they will follow contour lines.

When the dip angle is small and the area is large it is difficult to obtain dip measurement of the necessary accuracy with a clinometer, and outcrops may be situated far apart with hills between. In such a case it may be necessary to work with differences of height, for which an aneroid is useful. In country of strong reliefs which is unmapped some such aid is necessary. The accuracy obtainable depends upon the type of instrument, the weather and the range of height over which it is used. For relative heights taken in fine weather over less than a thousand feet in range the accuracy should be of the order of some 50 ft.

Next, the question of the measurement of the thickness of beds must be considered, and here it is simpler to begin with the cliff in Fig. 14. In such a case where the face is

nearly vertical and yet accessible a simple way is to measure directly with a tape, an instrument which should be in the equipment of every mapping geologist.

Where the cliff face is not accessible a method such as that given in Appendix III may be employed.

Turn now to the case of dipping beds outcropping at the surface of flat or sloping ground, the thickness can be calculated from the true dip and the width of outcrop.

In a bed or series of beds which is comparatively thin and whose outcrop is clearly marked on the surface of the ground the calculation is simple. It can be paced or taped across on the ground and its angle of dip measured.

The thickness can then be determined either by plotting to scale or by a formula.

If the outcrop is on a horizontal surface the expression is:

Thickness of Bed = Width of Outcrop × sine angle of dip.

If the outcrop is measured along a slope the formula must be altered to:

Thickness of Bed = Width of Outcrop × sine angle between the slope of the ground and the bed.

This angle is obtained by measuring in the field the slope between the top and bottom boundaries of the bed and adding or subtracting it from the dip according as the angle is an elevation or depression.

In the case of thick beds and small angles of dip the boundaries will commonly be far apart and invisible from each other, in which case a note of the height above sea-level of the two boundaries should be made in order to obtain the slope between them.

It should be noted that if the width of outcrop is being measured from a map the horizontal distance and not the slope distance will be obtained. The error due to neglecting this will be less than 5 per cent. up to an angle of slope of 15°, and unless the outcrop and the dip are very clearly defined the errors in their measurement may easily be of the same order of magnitude. If an apparent dip and not the true dip is used for the calculation the formulæ still

hold good provided that the width of the outcrop is measured in the same direction as the apparent dip.

Closely allied to the problem of finding the thickness of beds is that of finding the depth at which a bed of uniform thickness will be met with in a boring at any one spot. It means, in fact, finding the *vertical* thickness of the strata instead of the actual thickness. In the case of an outcrop on a level surface this will be given by:

Width of Outcrop $\times$ tangent of the angle of dip,

and in outcrops on sloping surfaces the same modifications must be made as in the similar cases just considered.

CHAPTER IV

SURFACE AND OUTCROP

IN the last chapter it was seen that it is usually possible to get a measurement of the dip of strata by direct or indirect means at certain points of its outcrop on the surface, but what the field geologist is really aiming at is to plot on his map the boundaries of the outcrop, the courses of which naturally depend also on the surface relief.

Whenever possible, the best way is to trace actually the outcrop of a bed over the surface of the ground, to "walk up" the outcrop in fact, and the cartographic methods of plotting from a few measurements only, which are the subject of this chapter, should only be used when for lack of opportunity or on account of the difficulty of the country the mapping of boundaries cannot be done on the ground itself.

In tracing the outcrop of a bed over the surface a variety of methods are used to identify the boundaries, some of which are briefly referred to at the end of this chapter, but in any case the plotting of the results should be done in the field. Where a good topographical map is available the procedure is simple enough, the various points on the boundary being inserted on the map with reference to surface detail at hand. If the country is unmapped or if the map is lacking in precision or in detail the boundaries have to be surveyed, the simplest method being a compass traverse with pacing as the means of measurement of distance. Naturally this involves a much greater expenditure of time, since the tracing of a boundary means a good deal of roaming to and fro over its probable route in order to fix it, so that where there is much difficulty in tracing

the line it is usually preferable to make the survey a separate operation altogether, working on marks left during the geological reconnaissance.

This "walking up" of outcrop is usually simple in country of bold relief, or of arid climate, or where the beds are of marked character, but very often it may be impossible to determine the boundary without a break, from surface indications, especially where there is dense vegetation, or thick soil, or much alluvium. In such cases a shorter means of plotting the probable line of outcrop may have to be used and, provided that the strata

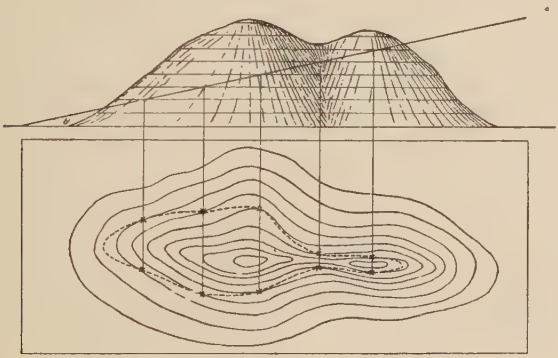


FIG. 21.—OUTCROP OF A STRATUM.

The intersection of a plane with a complex curved surface; exemplified in the case of a thin stratum and a topographical feature, a hill. The trace is the course of the outcrop of the stratum.

have a constant dip over the area dealt with, the result may be very near the truth. A problem in solid geometry then arises: to find the intersection of an inclined plane —the stratum in question—with a curved surface, the surface of the ground. Whether the surface of the ground is simple or complex makes no difference to the problem, provided that the map accurately shows the surface.

Fig. 21 shows the problem in its simplest form. A hill in elevation is cut by a plane dipping at an angle θ, and below is the plan of the hill showing the "trace" of the intersection of the plane with the surface: in other words, the surface outcrop of such a plane.

Consider the plan of the hill. Taking any one contour it is clear that the trace or outcrop cuts it in two places, one on each side of the hill. Joining these two points by a straight line, for each contour it is found that such lines are parallel to one another, and, indeed, they represent the strike of the bed, which, if the direction of dip is constant as postulated, must itself be constant. This fact gives the clue to a simple graphic method of plotting the outcrop of a bed with constant dip on a contoured map. The method is thoroughly treated in most books on geological maps and will only be referred to briefly.

Fig. 22 is a contoured map of a small area. Suppose, first, that a single measurement of the dip of the bed has been made at the point A where it outcrops on the contour 500 ft. and that elsewhere on the area the outcrop is not at all well defined. If there is reason to believe that the dip is constant over the area the outcrop can easily be plotted. First draw a horizontal line through A in the direction of strike: it passes through the air, so to say, across the valley to the south of A, but meets the ground surface again at the 500 ft. contour near the lower edge of the map. This will then be a point of outcrop.

The bed is dipping up the valley at an angle of, say, 6°, and it will have sunk 100 ft., that is to say, to the next contour level, in a certain distance commonly known as the horizontal equivalent for that angle. This distance can be found either by drawing a section to scale as is done below the map or more simply by multiplying the vertical distance dropped, 100 ft., by the cotangent of angle of dip, 9.5, giving 950 ft. as the horizontal distance required.[1] By measuring off 950 ft. from A along the direction of dip and drawing a strike line parallel to the first one, a line on the surface of the bed at a height of 400 ft. is obtained, and wherever it intersects the 400 ft. contour there should be an outcrop. Similarly points of outcrop for the 300 and 200 ft. contours are found, and the complete

[1] Or, by using the approximate table given in Appendix III, the horizontal equivalent is found to be 1,000 ft.

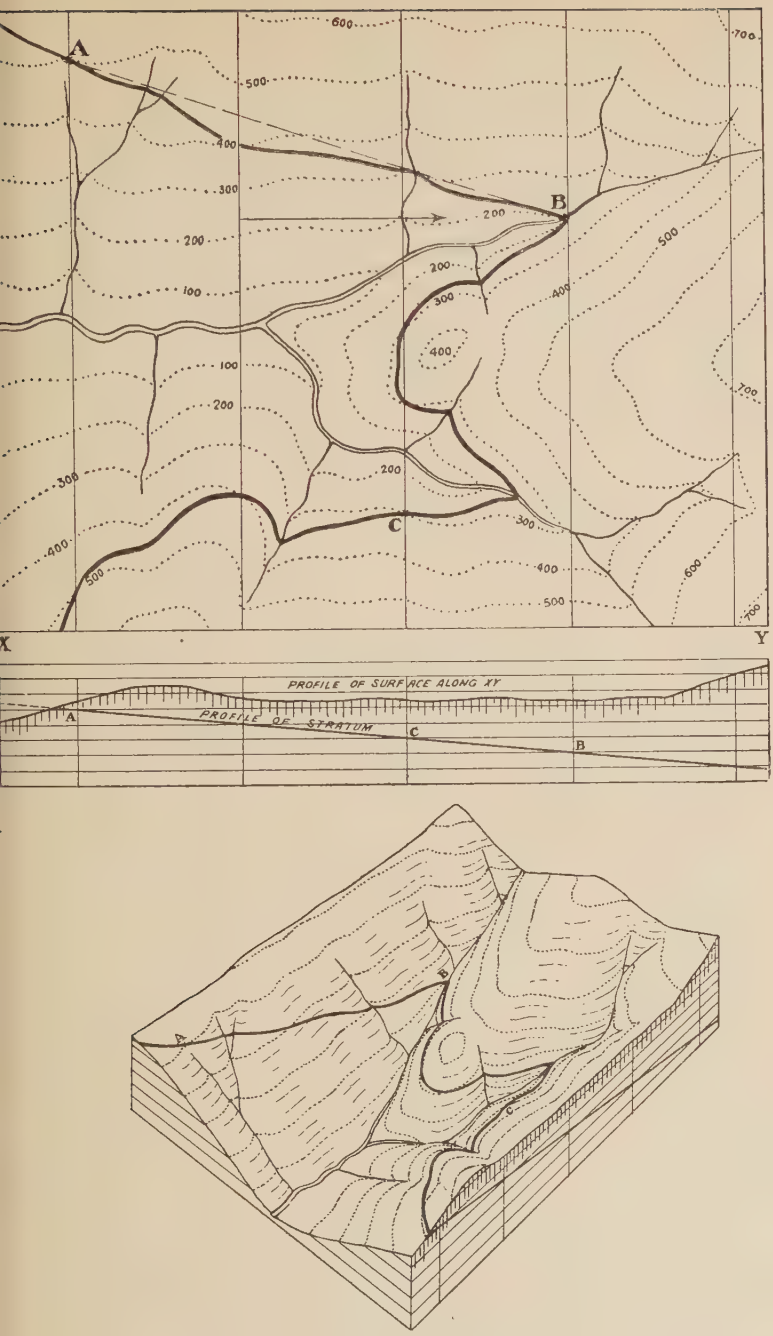


FIG. 22.—MAP AND BLOCK DIAGRAM OF THE OUTCROP OF AN INCLINED STRATUM.

line of outcrop is drawn in between these points by carefu reference to the trend of the contours. It will be note that the 200 ft. strike line touches the 200 ft. contour onl in one place B, and that the 100 ft. strike line nowher touches the 100 ft. contour.

It should be observed that these parallel equidistan strike lines which have been drawn across the map ar nothing more nor less than contour lines for the surface o the stratum, referred to the same datum level as the tru ground contours. Consequently, where a ground contou intersects a stratum contour of the same value the bed will appear at the surface: where a ground contour intersect a stratum contour of lower value the stratum is below the surface: finally, where the ground contour intersects a stratum contour of higher value the stratum was originally above the present surface and has been removed by erosion.

This method of regarding strike lines drawn at differen vertical intervals as "sub-surface" contours is often usefu in elucidating the problems of solid geometry which are constantly coming up before the field geologist. As has been seen, for a constant dip these sub-surface contours will be equidistant parallel straight lines. If the dip increases in amount but remains constant in direction, the sub-surface contours will be closer together but always straight lines. Further, if the direction of dip alters, the sub-surface contours will become curved. Such complications will be dealt with when folded strata are considered. Only a thin bed has been considered here: if the bed is a thick one, of which the upper face has been traced, then the lower face will have to be done separately since the two boundaries of outcrop are not parallel to one another. In Dr. Elles's *Study of Geological Maps* there are some good examples of such cases with beds of considerable thickness.

So far it has been supposed that a complete measurement of the true dip and its direction was made at A, from which the whole outcrop has been plotted, but what is more likely to happen perhaps is the converse, that is to

say, the outcrop has been recognized at a few places, but nowhere was it possible to get a reliable measurement of dip and direction.

Suppose that the bed was recognized at A and then again at B. From these two outcrops can be got an apparent dip, i.e. a fall of 300 ft. in the distance AB and in that direction. This by itself is not sufficient to determine the true dip and direction, but if during further search over the area a third outcrop is found at, say, C, this gives data for another apparent dip in the direction CB (or AC), and by the methods given in the previous chapter the true dip and direction can be found.

Or there is another way of setting to work in the field. Supposing, for instance, the bed is first met with at C on the 300 ft. contour. Then, if at any other point on the same contour this bed is again recognized, the line joining those two points will be the direction of strike. The amount of the dip and its direction can be found at once when the bed is recognized on some other contour, say at B.

In areas where the dip of strata is small in amount and constant, as in many parts of East Anglia, such a method of finding the dip is practically the only one possible. Conversely, where the dip angles are high they are more easily measured, but at the same time are less likely to be constant.

It is clear that these methods depend on the proviso that the dip is constant in amount and direction over the area in question: they will break down if there is any folding or change of dip. The assumption of constancy of dip is usually made on evidence which is less local, that is to say, on the knowledge that in adjacent districts the beds have a constant dip or that other beds above and below the one in question have been shown to have a constant dip.

But one must be cautious in accepting the constancy of dip over an area, for even where there is what is sometimes known as a "regional dip," that is to say a general

inclination of the beds in one direction, the average dip over a long distance may be a very different thing from the amount of dip over a small part of it. In other words, there may be low folds or warpings of the strata which may be of considerable importance. It is not uncommon, for instance, to find petroleum-bearing beds with this structure, the oil having been trapped in the slight folds or terraces at places along the general dip.

In many series of strata there are beds which are practically constant in thickness over large areas. A bed of this type is of great value in determining dip where more direct methods fail.

In the last chapter it was shown how the thickness of a bed could be found from its dip and width of outcrop. Therefore the dip can be found if the thickness and width of outcrop are known. Taking the simplest case where a bed outcrops on a level surface, suppose the bed is known to be 200 ft. thick and its outcrop 1,500 ft. on the level surface. The ratio 200 : 1,500 is then the sine of the angle of dip, or $\cdot 13 = \sin 7\frac{1}{2}^\circ$. In a less simple case the outcrop may not be on a level surface but over hill and dale. Suppose that its upper face outcrops at the 500 ft. level and its lower face a mile away at the 800 ft. level. The width of outcrop is then 5,280 ft. at a slope of $\frac{300}{5,280}$. The ratio is the tangent of the angle of slope between the upper and lower faces, which from the tables is found to be 4°. Then $\frac{200}{5,280}$ is the sine of the angle of dip measured from the line joining the upper and lower face outcrops, and equals $2\frac{1}{2}^\circ$. To get the angle of dip from the horizontal add the 4°, giving an angle of dip of $6\frac{1}{2}^\circ$. It is important to note, however, that before the width of outcrop can be measured the general direction of strike must be known so that the measurements can be made directly across the outcrop. Note also that the term "width of outcrop" is the length of the straight line joining the upper and lower face outcrops and is not the distance

measured over the surface of the ground. Thus, if the lower face outcrops on one side of a hill and the upper face on the other, the width of outcrop is the direct line through the hill, not over its surface.

This method of finding the dip of a bed from a knowledge of its thickness may be of great value where the dip is known to be altering, as in the case of a fold, and where several consecutive measurements of dip are required to determine the degree of folding.

Returning again to the problem of tracing the outcrop of a bed from its dip, it is interesting and of some importance to note how the shape of an outcrop in a valley depends upon the amount of dip, assuming the direction of dip is more or less parallel to the line of the valley.

When the dip is up the valley the outcrop will always be of V shape up the valley, as shown in Fig. 23, *e*, *f*, *g*. When the dip is down the valley the outcrop will also be V shaped, but whether up or down the valley depends on the amount of dip. If the dip is greater than the slope of the valley then the V outcrop will always point down, but if the dip is less than the valley slope it will be a V outcrop up the valley. Fig. 23 shows these variations in a diagrammatic way, and Figs. 24, 25, and 26 less diagrammatically.

When the direction of dip is not down the axis of the valley but inclined to it, the V shape of the outcrop will be modified, one limb of the V being shorter than the other.

It should be clear from the foregoing that the dependence of the form of the outcrop on the surface relief is of great importance to the field geologist and an understanding of the nature of that dependence will illumine his field work considerably.

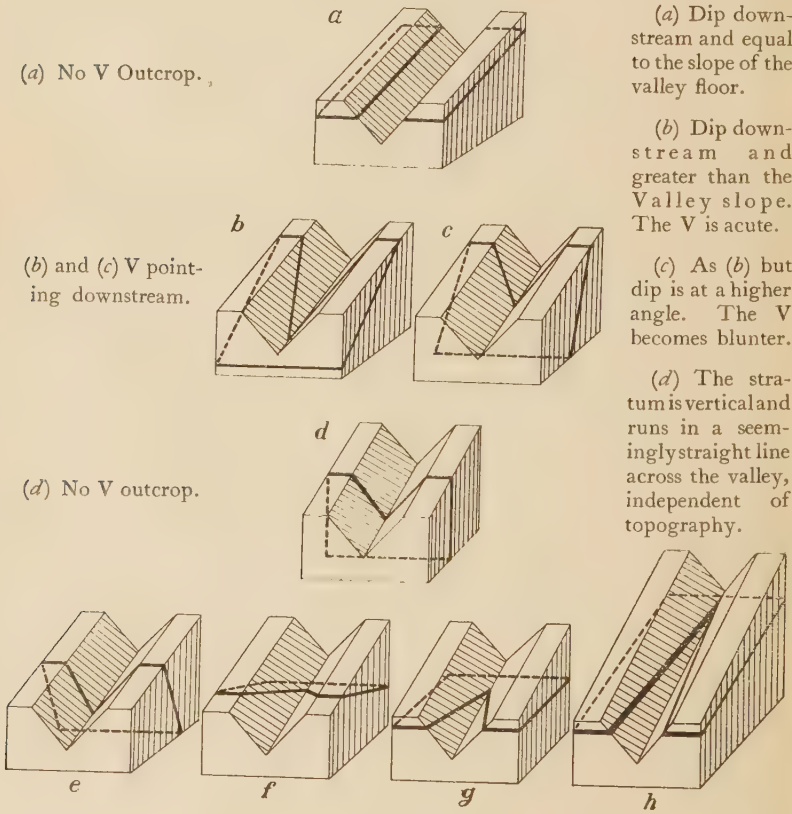
Reference may be made to a few of the more practical points which arise in the search for outcrops and boundaries. Naturally, this search is a simpler matter in country with strong relief and where the strata are more steeply tilted, if only because there will be more outcrops in a given area.

The covering of boundaries by soil and drift is also likely to be less in hilly country than in level country, where the soil is less disturbed by erosion. Again, in hilly country there is very little local deposition by streams, and there

(*a*) No V Outcrop.

(*b*) and (*c*) V pointing downstream.

(*d*) No V outcrop.



(*a*) Dip downstream and equal to the slope of the valley floor.

(*b*) Dip downstream and greater than the Valley slope. The V is acute.

(*c*) As (*b*) but dip is at a higher angle. The V becomes blunter.

(*d*) The stratum is vertical and runs in a seemingly straight line across the valley, independent of topography.

V pointing upstream.

(*e*) The dip is upstream at a high angle: the V is blunt.
(*f*) As in (*e*), but the dip is at a less angle: the V becomes sharper.
(*g*) The stratum is horizontal: the V is sharper still.
(*h*) The stratum now dips down-stream, but at a less acute angle than the slope of the valley: the V is very acute.

FIG. 23.—A SERIES OF DIAGRAMS TO SHOW THE FORM OF OUTCROP OF A STRATUM IN A SECTION OF A VALLEY WITH UNIFORM SLOPE OF ITS STREAM BED. THE STRATUM MAY BE CONSIDERED AS A PLANE ROTATING ON A HORIZONTAL AXIS ACROSS THE VALLEY; DURING A COMPLETE REVOLUTION (GIVING EVERY DEGREE AND BOTH DIRECTIONS OF DIP) IT PASSES THROUGH THE STAGES SHOWN.

in general the best plan is to follow up the beds of streams where the underlying rocks are most likely to be exposed. In thickly forested regions there are unlikely to be any exposures at all except in the streams, at any rate on the more level parts.

FIG. 24.—OUTCROPS OF BEDS DIPPING DOWN SLOPE.

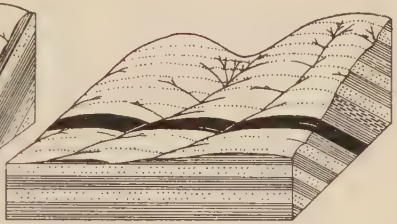


FIG. 25.—OUTCROPS OF BEDS DIPPING UP SLOPE.
An example of Fig. 23*f*.

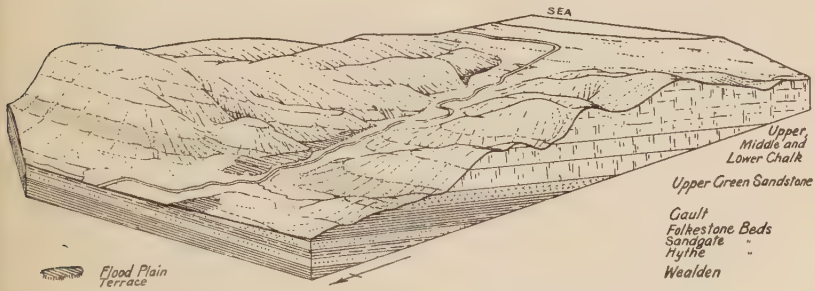


FIG. 26.—LOWER REACHES OF THE RIVER ADUR, SUSSEX.
1″ sheet 318 N.S.

The various members of the Cretaceous System dip to the south. The more resistant beds, the Chalk and Upper Greensand, form high ground. Points to be noticed are:—the V-shaped outcrops pointing down stream: the obscuring of the outcrops by the alluvial deposits of the river: the "water gap" formed by down-cutting of the river: the flood plane terrace coeval with those of the Thames and many other rivers.

In open flatter country the stream beds are usually of less help, tending to obscure the outcrop with alluvium, and often enough the soil is of embarrassing thickness. It is as well, therefore, for the geologist to become reasonably acquainted with the characteristics of the soils derived from different rocks. There are few rules to go by beyond

the broad and rather obvious ones and even these may be misleading. Thus, a sandy soil may denote a sandstone underneath, but it may also be alluvium derived from distant rocks. But if the soil be actually derived from the rock in place, a little digging with the point of the hammer will often give indications never apparent in the top soil. The residue of undecomposed boulders in a soil may be of great assistance in diagnosing the parent rock underneath, but caution is necessary in accepting such evidence. Some rocks, such as granite and some

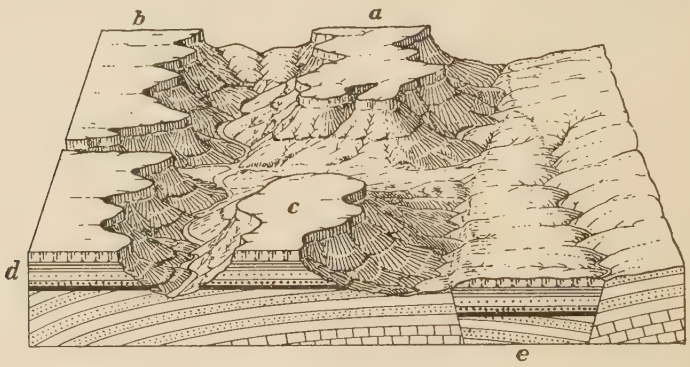


FIG. 27.—SOME MODES OF FORMATION OF OUTLIERS.

(i) By Denudation.

In the figure, the limestone *a*, *c*, being entirely isolated from the main outcrop *b* by intervening older beds, forms outliers. In the case of *c* the whole block of the younger horizontally bedded series is isolated by a surrounding outcrop of the older folded series, and therefore forms an outlier of the series *d*.

(ii) By Faulting.

The block *e* has been faulted down so that the younger series is isolated. A cross-fault, such as one in the plane of the section, or a diminishing throw of the faults towards the observer and removal of the younger series by denudation in that direction, must be assumed to complete the isolation.

lavas, for instance, decompose into a soil with a considerable admixture of loose fragments of the parent rock, which are sometimes referred to as "float": other rocks decompose more thoroughly. In any case such fragments may be derived from other horizons, and especially on steep slopes or near river beds it is advisable to be thorough in establishing the fact that the fragments are not derived from elsewhere by transport.

Again, certain rocks form better indicators than others, and of these limestone is a conspicuous example. This is partly due to its appearance being very different from

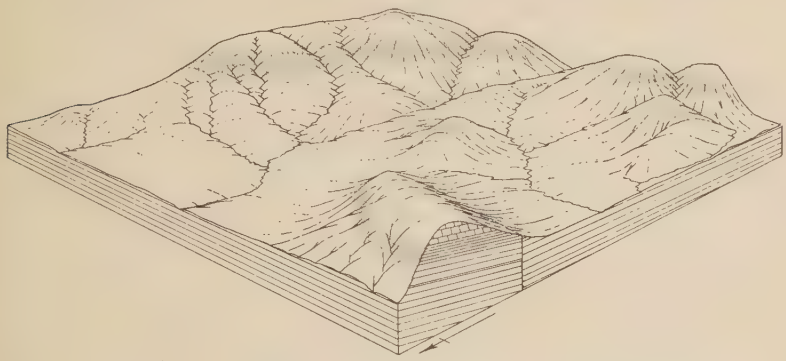


FIG. 28.—OUTLIERS FORMED BY DENUDATION OF NEARLY HORIZONTAL STRATA, NEAR CHELTENHAM, GLOUCESTERSHIRE.

Sheet 44 Old Series. Area shown 66 sq. miles.

In the background is part of the tableland forming the Cleeve Hills. Upon a floor of Lower Lias Clay rest Marlstone (Middle Lias), Upper Lias Clay and Inferior Oolite. Bredon Hill (foreground) and Oxenton Hill (right foreground) are capped with Oolite. These and other smaller hills of Middle and Upper Lias form outliers of the main mass of Jurassic rocks. A fault running E. and W. on the south of Bredon Hill lets down Oolite against Lower Lias Clay.

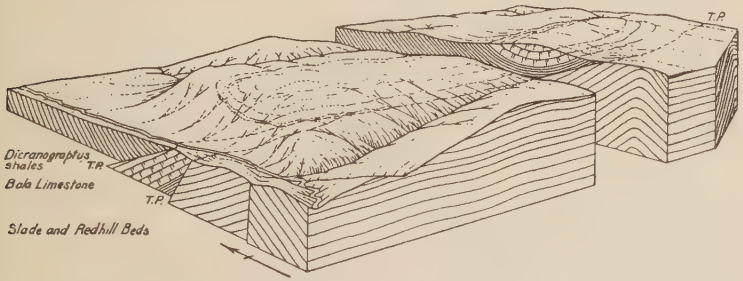


FIG. 29.—OUTLIER DUE TO FOLDING. NEAR LLANDOWROR, CARMARTHEN.

Sheet 229 N.S. Area shown $1\frac{1}{3}$ sq. miles.

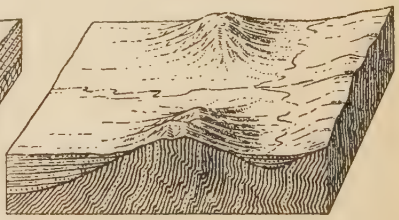
A strip of Bala limestone lying along the axis of a fold has been almost completely isolated by denudation. The synclinal mass has been overthrust to the south, over-riding a block of Bala limestone which has itself been thrust at a high angle against younger beds. All these beds are Ordovician (Bala Series).

the shales and fine sandstones with which it is usually associated, but still more to the fact that the formation of a limestone is generally due to comparatively stable con-

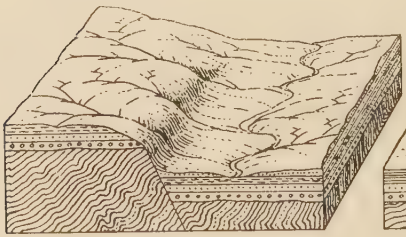
ditions in the sea in which it was laid down, so that a layer is often spread widely and uniformly. When the rock is indurated its characteristics are even more markedly different from those of shales, and since its constituents

(*a*) By denudation of a dome (only half is shown).

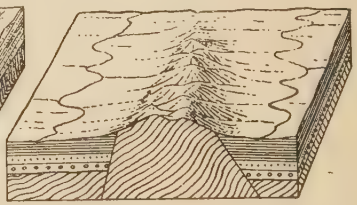
(*b*) By denudation down to an uneven surface of an unconformity.



(*c*) By incomplete burial by younger strata.



(*d*) By simple faulting.



(*e*) By horst faulting.

FIG. 30.—DIAGRAMS TO SHOW SOME MODES OF FORMATION OF INLIERS.

are different it gives sustenance to a different type of vegetation. When massive a limestone is perhaps the easiest of all outcrops to follow, since it tends to form bold exposures and a type of drainage in marked contrast to that of other rocks.

There are some cautions to be remembered in making

observations from superficial characters. Many rocks, for instance, especially thinly laminated types, are liable to show the phenomenon of soil creep to a greater or less extent, so that the external surface to a depth of several inches, or even feet, show the laminæ distorted out of the

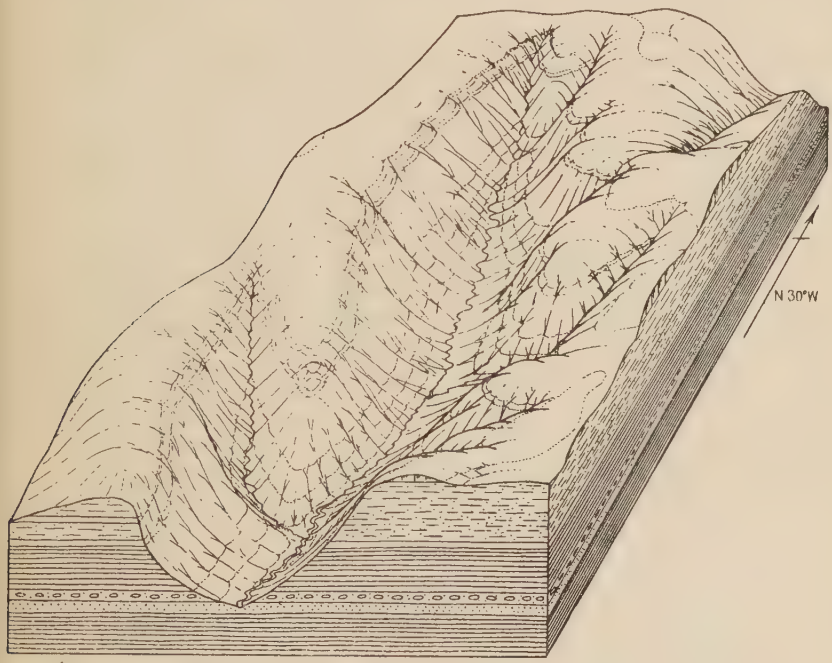


FIG. 31.—FARNDALE, VALLEY OF THE RIVER DOVE, EAST YORKSHIRE.

Sheet 48 N.S. Area shown, 17 sq. miles.

In this district the Jurassic rocks are greatly folded along an East and West axis just beyond the extreme distance in the diagram. The beds here dip at a small angle southwards. Dip streams, such as the Dove, have cut down through the Oolite so as to expose the whole Liassic succession in their valleys. The outcrops so formed are leaf-shaped and entirely surrounded by Lower Oolite, and are thus inliers due to denudation. [The southern end of the outcrop has been cut off so as to give a section.]

The diagram also illustrates V-shaped outcrops. At the heads of the valleys where the slope of the stream bed is greater than that of the beds and in the same direction, the V's point upstream; where slope and dip are equal, outcrops and stream are parallel and there are no V's, as in the middle of the diagram; where the slope of the valley floor decreases in its lower reaches, so as to become less than that of the beds, as in the foreground, the V's point downstream.

Succession of beds from below upwards:—Lower Lias; Sandy Series and Ironstone Series, Middle Lias; Upper Lias; Estuarine Beds with Eller Beck Bed (not continuous) and Grey Limestone, Lower Oolite.

plane in which they originally lay, from which event one might infer a dip quite different from the true one. Massive blocks projecting from the soil may have been detached from their beds and tilted at various angles. It is perhaps as well to mention the danger of mistaking the cleavage of slaty rocks induced by pressure for the real bedding planes, or of being misled by current bedding in sandstones; but both can occur to a marked degree of simulation. The original bedding can usually be found in slates by noting streaks of slightly coarser grain or different colour, and sometimes by layers of organic remains. Current bedding on a large scale when observed only in a small cutting can give a quite false idea of the true bedding planes, and even these planes when found in a large quarry or river cutting are likely to be of only local significance.

In this chapter a number of diagrams is given to illustrate the formation of outliers and inliers. An outlier is an outcrop of rock which is entirely surrounded by geologically older rocks: an inlier is the converse, being an exposure isolated from its main outcrop by geologically younger rocks. It should be noted that an outlier is never continuous with its main outcrop, whereas an inlier is connected underground with its main outcrop unless faulting causes discontinuity. Thus any mass of rock, from a single bed to a whole series, may form an outlier or inlier if it fulfils these conditions. The more common occurrences are those due to denudation, where gently inclined beds have been dissected by streams so as to give rise to hills capped by isolated outcrops, as in Fig. 28. The One-Inch Geological Maps of the Cretaceous and Jurassic of England provide many examples. Folding and faulting are other agents responsible for isolation of outcrops.

CHAPTER V

FOLDS

THUS far there have been considered merely strata which, over the area of measurement, have been tilted at a constant angle, but general observation shows that this is not common over large areas. Indeed, since every bed is laid down horizontally, or approximately so, and tilting is caused later by distortion, it is obvious that the dip cannot be constant over a large area, but must vary with the degree of warping or bending from place to place.

Folding may be imitated by pressing together material, such as a tablecloth, from either end; this will induce in the material a series of waves more or less symmetrical. This is the simplest type of folding, and the tops or arches of the waves are known as anticlines, while the troughs are called synclines, the axis of folding being the line along the trough or arch. By using plasticine or modelling clay and varying the consistency of different layers, it is possible to imitate rock folding to almost any extent and produce complicated structures such as occur in nature.

Some of the variations from the simple symmetrical folding consisting of successive anticlines and synclines are shown in Figs. 34 to 39, which are quite diagrammatic: denudation is active throughout the slow formation of a fold, planing down and dissecting a crest as it rises, so that the land surface will, in general, be like that shown in Fig. 44. It is important to realize that the magnitudes of folds in nature may vary from the almost microscopic folding of highly contorted rocks to mountain-building folds many miles in length and thousands of feet in height. The folds of the South-East of England may be instanced

as a case of comparatively symmetrical folding over a large area, the syncline of the London Basin being flanked by the Wealden anticline, their axes being parallel.

Asymmetrical folds are common in the older rocks to the West of England, but are usually rendered much more complex by the occurrence of actual breaks or "faults."

An interesting case of a monoclinal fold of large size is to be seen in Australia, where the Blue Mountains to the West of Sydney are capped by a dense sandstone over a thousand feet in thickness which, at the eastern end of the plateau, is tilted steeply for over a mile: thus, the upper surface is brought down nearly 2,000 ft. and then continues more or less horizontally to the sea coast.

The monoclinal fold is evidently a type of asymmetrical fold with one limb of the anticline much more steeply inclined than the other, and is caused usually by the slow depression of the area on one side of the axis and not to lateral compression.

Variations in the intensity of the fold-producing forces and in the resistance will naturally give rise to many types of asymmetry of which the simple overfold, leading to the recumbent fold, is a typical form. Again the direction of compression may vary at different places or at different periods, and consequently one system of folding may be superimposed upon another. Further, the intensity of the compressing forces may vary along the line of the axis, so that folding is more intense in one place than in another, giving rise to pitching folds or elongated domes. That the axes of such pitching folds will not normally be parallel may be shown by producing them with a tablecloth. In a word, the field geologist must expect to meet with a great variety of fold types, the general characteristics of which are adequately treated in textbooks of geology.

What one is chiefly concerned with here is how to recognize and measure them in the field, and inasmuch as folded rocks are the rule rather than the exception the geologist may be said to be dealing with folding as the normal structure in his field work.

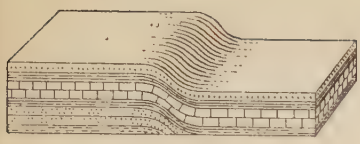


Fig. 32.—Monocline.

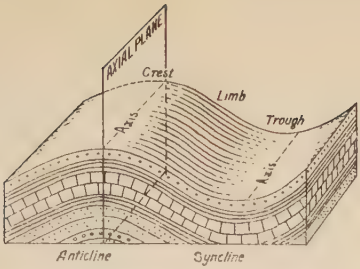


Fig. 33.—Symmetrical Anticline and Syncline.

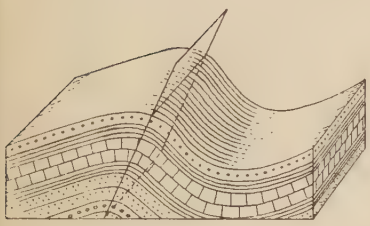


Fig. 34.—Asymmetrical Anticline and Syncline.

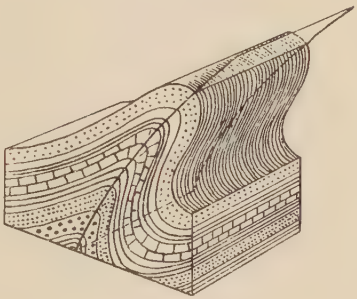


Fig. 35.—Overfold with curved Axial Plane.

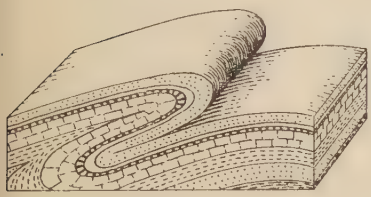


Fig. 36.—Recumbent Fold.

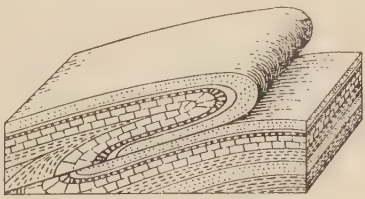


Fig. 37.—Recumbent Fold passing into a Thrust Block.

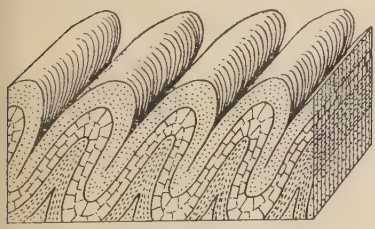


Fig. 38.—Isoclinal Folds.

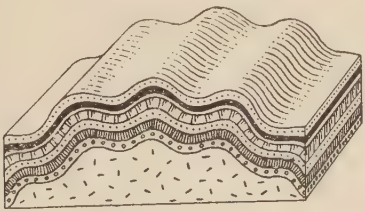


Fig. 39.—Anticlinorium.

Indeed, for certain applications of geology, such as in the search for oil-bearing areas, the field worker is largely concerned with the search for and careful mapping of anticlines, the dome-shaped type being the most sought after. The reader should be reminded at this stage that the study of geological maps is of the greatest help in assisting the field worker to recognize in the field structures of this kind, and he should get all the practice he can in interpreting, either visually or by drawing sections, the data of geological maps of folded areas.

As was noted in the case of strata with uniform dip, the measurements are much simpler to make when there

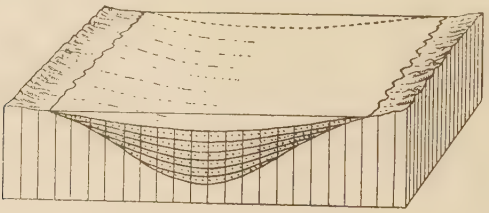


FIG. 40.—A GEOSYNCLINE.

A large region between two land masses sinks, and sedimentation, involving a series of overlaps, keeps pace with submergence.

are exposures which are more or less vertical, as in quarries or sea cliffs or in mountainous country.

One may distinguish, further, between the comparative ease of mapping folds of small amplitude and the difficulty experienced with those of large amplitude where the repetition of beds due to the folding may be either very distant or not observable at all. Another difficulty in mapping folded strata comes from the covering of exposures by other material, either soil, drift, or later deposits laid down unconformably upon the folded strata.

To begin with the case of a simple and more or less symmetrical fold exposed on a sea cliff as in Fig. 41. One can see at a glance the general type of folding and note also that the appearance of the fold is altogether altered by the direction in which the section cuts across the fold.

A section along the axis of the fold will show apparently level beds, and in general the apparent dip of the limbs increases as the section veers round towards perpendicularity with the axis until, when the section is at right angles to the axis, the true dip of the limbs is exposed. Thus, the curvature of the cliff face may have the effect of making a symmetrical fold appear unsymmetrical or vice versa.

Clearly, therefore, it is of importance to determine the direction of the fold axis, and whether the axis is horizontal.

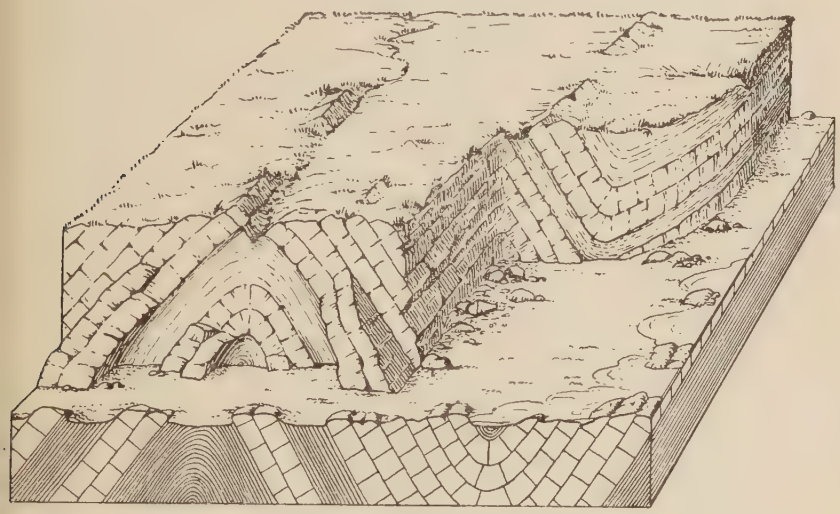


FIG. 41.—MARINE DENUDATION OF SMALL FOLDS.
The syncline viewed from the distance appears to be asymmetrical.

In the case of a simple fold with horizontal axis the line of the axis will be the same as the line of strike, which can be determined by the methods described in the last chapter. But in the case of "pitching" folds, when the axis of the fold is inclined, the line of strike is not parallel to the axis; indeed, the strike directions on each limb of the fold will no longer be parallel, but will converge. (Another way of putting it is, that in such a case the true dips on either side of the fold will not be in the same direction.) The axis of the fold will be somewhere between the two strike directions, and if those directions are

measured at corresponding places on the limbs of the fold which is presumed symmetrical, the direction of the axis will bisect the angle made by the converging strike lines.

There is, of course, no certainty that the axis of folding is a straight line, but it is commonly so over small distances since the cause of folding is usually pressure along a line rather than at a point. The analogy of the folds in a tablecloth produced by pushing (*a*) with one finger and (*b*) with a long lath, is useful here. On the other hand, if one interposes a heavy object, such as a vase, in the line of the folds they will tend to be concentric with obstruction, and if there are several such obstructions the plan of the folding will be crenelated or wavy.

Whether the fold axis is straight or sinuous cannot be determined from a vertical section. Mapping of the flanking beds on either side along the course of the axis will give information on this point. If the fold is asymmetrical the axial plane (Fig. 34) will be inclined: a vertical cross section will show this, but, failing that, dissimilar dips on either side of the axis, in the same group of flanking beds, will indicate asymmetry. The axial plane, especially in the case of overfolding, is likely to be curved (Fig. 35), but since only a very small part is ever likely to be seen in a vertical section the curvature will not be obvious.

Again, there are certain phenomena, especially prominent in areas of intense folding, such as the pinching out of soft strata along the limbs of a fold and movements towards the crests and troughs which can be observed in a vertical section and are not easily recognizable in a horizontal one. It will be noted also that with intense folding, especially in the case of fine-grained rocks, there is often a secondary folding of small amplitude caused chiefly by the re-arrangement of the small particles. Such secondary folding is likely to be misleading where the exposure is only on a horizontal surface.

But it must be understood that when the folding is very intense, amounting to contortion of the beds, the ordinary principles of measurement hardly apply and little

can be done beyond fixing the general trend of the fold axes.

Consider next recognition and measurement of folds in the case where there are no vertical exposures and nothing

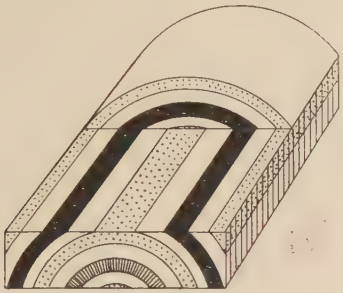


FIG. 42.—SIMPLE ANTICLINE, DENUDED (FOREPART) TO A HORIZONTAL PLANE SURFACE.

The outcrops of beds are parallel bands.

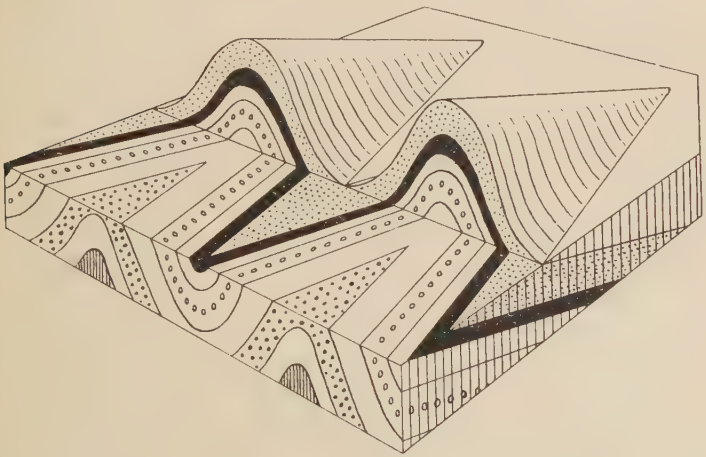


FIG. 43.—DIAGRAM OF PITCHING ANTICLINES AND SYNCLINE, DENUDED (FOREPART) TO A HORIZONTAL SURFACE.

The outcrops of beds trace a zig-zag course.

but surface outcrops and indications as a guide, the first clue to the existence of folds is the repetition of the outcrop of the same bed. As will be seen later, this can also be due to the occurrence of a fault and it is not always easy to distinguish between the two, but one characteristic of

a fold, not often found in the case of a fault, is that the dip of the beds is in the opposite direction on either side of a crest or a trough, so that if the repeated bed has a surface dip in contrary directions the inference is that one is probably dealing with a fold.

Somewhere in between the repeated beds there will be a single bed, with little or no dip, which represents the trough or the crest of the fold, and which of those two it is will be indicated by the dip of the beds on each side, which will be inwards in the case of a syncline and outwards for an anticline.

If there is no evidence as to which way the dips are running, then it is possible to recognize the anticline by the fact that the central bed is older than the flanking beds and vice versa for the syncline, unless one happens to be dealing with the somewhat rare case of complete inversion of beds.

In the surface presentment of a fold there are no direct means of observing the nature of the fold, its amplitude and symmetry, and these will have to be deduced from surface measurements. To find the axis of folding is rather simpler than in the case of the vertical section, for it will be parallel to the strike of the beds for a horizontal axis and bisect the converging angle of the beds for a pitching axis if the surface of measurement is level.

If the surface is not level, then care must be taken to determine the strike lines of the beds, which, *ipso facto*, are the trends of the beds for a level surface. Thus, in the case of an axis at right angles to the top of a hill the outcrops of the repeated beds in a horizontal fold will diverge for a syncline and converge for an anticline, though the strike lines will be parallel.

It is clearly of importance, especially in beds of economic value, to be able to specify what type of folding is present, so that the depth of any bed below the surface at any given point can be calculated.

If it is possible to make a series of measurements of dip along the same bed, as it will be occasionally in country

of strong relief, the curve of the fold can be plotted between these points and extrapolated somewhat beyond the measurements, especially if they occur on both sides of a trough or

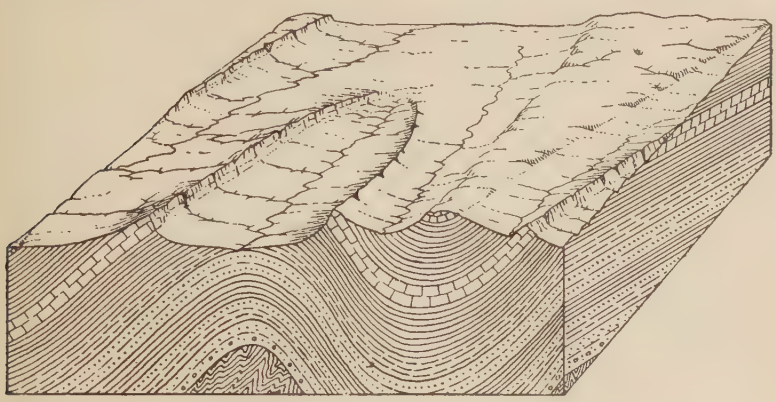


Fig. 44.—Pitching Anticline and Syncline.

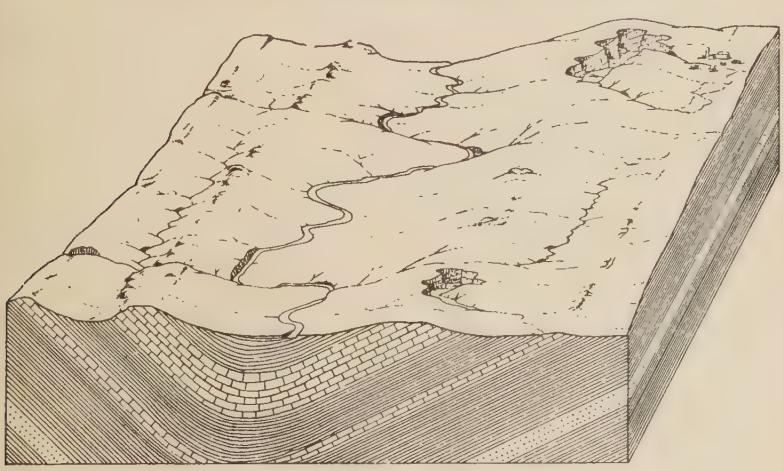


Fig. 45.—Asymmetrical Syncline, showing Exposures at various points at which Dips can be determined, and hence its Existence and Structure.

crest, but more usually a single bed cannot be followed though the dips of successive beds can be measured.

In such a case, if dips can be found only on one side of the anticline or syncline and the position of the axis is not known, the fold cannot be reconstructed with certainty;

but if similar beds are recognized on both sides the fold can be reconstructed with considerable accuracy from a consideration of the thickness of the beds.

Suppose, for instance, that dip measurements have been made as shown on Fig. 45. The dips point inwards to a point where there is no dip at all, the trough of the syncline, where there is a small bed which is not repeated. From

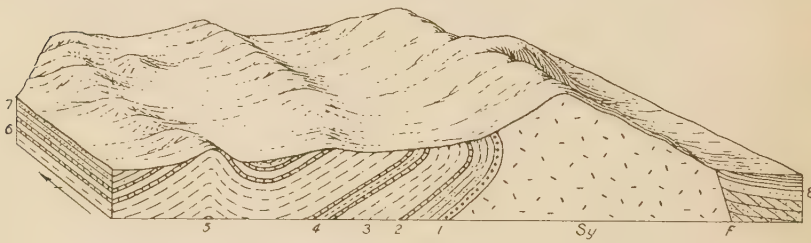


FIG. 46.—WORCESTERSHIRE BEACON, MALVERN. PART OF THE MALVERN HILLS.

8, New Red Sandstone (Trias); 7, Old Red Sandstone; 6–1, Silurian; 6, Aymestry Limestone; 5, Lower Ludlow; 4, Wenlock Limestone; 3, Wenlock Shale; 2, Woolhope Limestone; 1, Conglomerate with Pebbles of Subjacent Syenite (Ancient Beach); Sy, Syenite; F, Fault.

Sheet 55 S.E. Old Series. Area shown, 2¼ sq. miles.

Part of the great inlier of Silurian rocks outcropping continuously in a narrow band from near Ledbury in the south to the River Teme in the north.

On the east a north and south fault, traceable for 20 miles, lets down Triassic beds against the pre-Silurian Syenitic mass which outcrops for 8 miles as a narrow belt of high ground. On the west Old Red Sandstone lies conformably on the Silurian. To the south, Permian and Trias cover the Silurian south of Ledbury, while to the north Trias and Old Red Sandstone close on one another and thus pinch out the outcrop.

Note.—The resistant syenite stands out as a long ridge of high ground. The Wenlock Limestone gives rise to a scarp along the greater part of its outcrop. The crest of a fold stands out as elevated ground, since it is protected by the parallel outcrops of Aymestry Limestone high up on either flank. The New Red Sandstone on the east being easily denuded forms a plain of low relief, whilst the Old Red Sandstone on the west gives rise to ground of somewhat higher relief. (The diagram does not extend far enough to show this.)

the width of the outcrop and the amount of the dip the thickness of each bed is calculated by the methods described in Chapter III. So one can begin to reconstruct the fold in the section below by plotting the dip of the first repeated bed, continuing it in a smooth curve under the surface, and then drawing in successive beds outwards from the centre in the same way.

If the fold is unsymmetrical, this fact will show on the surface by the beds on one side having a steeper dip and less wide outcrop than the corresponding beds on the other side. The procedure in making the section is the same as before, but the axial plane dips towards the steeper limb of the fold.

So far it has been assumed that a reasonable number of dips can be taken on either side of the bed and that the axis of the fold has been established in the field. But as a matter of practice this is not always the case unless the exposures are particularly good and the country very easy. Sometimes the existence of folds is not even suspected for some time in the field, and it is not until the measurements are all plotted and the resulting map thoroughly studied that the probable state of affairs underground is established; even then the final full plotting must often be only one of several possible solutions. It is only when the data collected cover a comparatively small area and when some of the evidence is very definite indeed that one can fully visualize the structure while on the ground, though in each succeeding visit to the locality after working over the earlier data the matter becomes clearer.

In a word, the field geologist is constantly collecting data which furnish him with a hypothesis, the hypothesis then leads to a search for further evidence which will either confirm it or render it untenable and give rise to a new one.

It is of great importance to the beginner in field geology to realize that he is rarely able to get a measurement just where he wants one, and that the evidence he is able to obtain is often of the most sketchy description and at first sight may appear to be nothing but a collection of disconnected data with all the links missing.

CHAPTER VI

FAULTS

THE rocks of the earth's crust may be likened to ice or pitch in that they will readily fold under a steady low pressure, but will break if the stress is applied suddenly or rapidly.

These breaks, known as faults, are very common phenomena in regions which have suffered much movement; since they have the same kind of origin they are usually but not invariably associated with folds.

The stresses producing the faults may be in the form of a tension, in which case the broken masses will tend to take up more space laterally, or of a compression, when they will tend to overlap and take up less space.

There are also differential movements which are of the nature of a shear stress, producing breaks which are like tears.

Faults can therefore be classified as tensional or compressional, shearing faults being a sub-type of the latter class.

The simplest type of all is that due to slight tension which, together with the force of gravity, produces a break and a fall of the beds on one side with respect to the other. Such a break is called a *normal*[1] fault and is illustrated in Fig. 47, which also explains the terms used to describe the parts of a fault.

Thus the vertical drop of one bed below the other is the *throw*, and since the movement in this case may not be truly vertical it may leave a gap between the broken

[1] This is a convenient term for a particular class of fault, established by long usage, but this class is not necessarily the most commonly occurring.

edges of the bed, the horizontal projection of which is known as the *heave* of the fault. The heave and the throw, in other words, represent the rectangular components, horizontal and vertical, of the actual movement which is a slide along the fault plane. This movement may extend eventually to thousands of feet, but it is normally accomplished in very small steps and over a long period. Owing to the enormous weight of the masses concerned the successive small slips are the commonest cause of earthquakes, and the effect on the beds themselves at the fault plane may be very marked. In the case of normal, tensional faults, the rock faces are usually smoothed and striated to

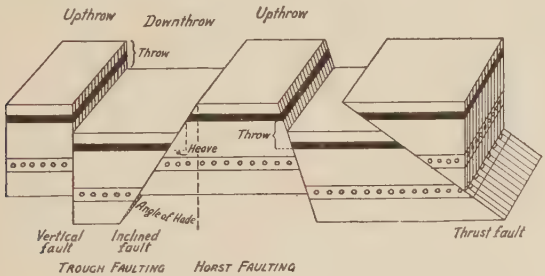


Fig. 47.—Diagram of Fault-Types.

form what is known as a "slickenside," but with compressional or reversed faults the rock on either side of the fault plane is often broken up into a *fault-breccia*. In either case considerable heat is generated, and it might be possible to determine whether any fault is active by taking earth temperatures in its vicinity.

The fault plane itself is rarely quite vertical, and its inclination to the vertical is known as the hade of the fault. Also, the expression "plane" should not be taken in the mathematical sense, since all fault planes, if traced in any direction, are found to be undulating surfaces. In compressional faults the hade may be considerable, but it is rarely above 20° in the case of tensional faults. The hade is sometimes referred to as the dip of the fault, in which case it may be measured from the horizontal plane.

The beginner is apt to be misled somewhat as to the

nature of fault planes from studying the formal diagrammatic figures of faults or the models of faults which are part of the equipment of most schools of geology. A common mistake in textbooks is that of representing a trough fault as a wedge of rock dropped down below its former position and lacking some of the beds altogether, a manifest impossibility. Also, for the sake of simplicity the hade of faults is usually made constant both in a horizontal and vertical direction, whereas in nature the inclination of the fault plane is always found to be variable in a greater or less degree both with depth and along the surface trace of the fault. The extent of faults both laterally and in depth is also a matter of interest. Some faults are undoubtedly deep-seated, but others are known to be shallow, the actual break dying out downwards with diminishing throw. No fault can extend indefinitely downwards, since at a depth of some 12 kms. the stresses producing fracture in the upper parts of the crust are relieved by rock flowage.

Again, the trace of the fault plane on the surface is usually shown in diagrams as a straight line, whereas in nature it is frequently curvilinear. In actual mapping in the field the course of a fault must be traced out just as is a geological boundary. When traced far enough a fault may either end abruptly against overlying rocks which have not been affected by the dislocation, or it may turn into a fold, or it may diminish in throw until it disappears. In rare cases, one block, faulted against another, may be so tilted that the side which in one place was the downthrow side becomes the upthrow side further along, the fault having no throw for a short distance at the change.

Faults are rarely visible at the surface of the ground as a sharp difference of level along the line of the fault, since the processes of erosion usually keep pace with the movement of a fault, while, if the fault is dormant or "extinct," they soon smooth over the line with soil or débris. They are, however, frequently marked by a line of springs.

Nevertheless, if the break has brought beds of different

consistency under the influence of aerial erosion there is often a change in the character of the land forms along the line of a fault, by which it may be recognized. Soft, easily eroded beds, faulted against much harder and older rocks, give rise to a marked topographical feature, a fault scarp (Figs. 30*d* and 49*d*), and strike streams at the junction are well developed. Sometimes faults which are otherwise well hidden become apparent when the light is shining horizontally across the line, which shows up as a slight change in the tone of the shadow.

In general, however, the position of a fault is recognized, not by direct means, but by deductions made from the displacement of beds on either side.

In vertical sections, such as sea cliffs, railway cuttings and quarries, faults may be readily recognized, either by the trace of the fault plane itself, or, if that is hidden, by the marked vertical displacement of the beds, and if possible the field geologist should begin his plotting of faults by examining such a vertical section and then tracing it by less direct means over the surrounding country.

A little consideration will show that the displacement of beds due to a fault will vary considerably according to the hade, the throw and the direction in which the fault plane runs. Some of these variations may be examined before an attempt is made to elucidate them in the field.

In a normal fault the downthrow side has suffered less erosion than the upthrow side, hence the beds on the downthrow side are younger than those meeting them on the other side of the fault. If the succession of beds is known or if the dip of the beds is determinable, this is a ready means of finding which is the downthrow side.

But it is clear that the apparent displacement of the beds as seen on the surface will depend on how the line of the fault runs in relation to the strike of the beds.

To study this variation it is convenient to classify faults into *strike faults*, which run parallel or nearly so to the strike, *dip faults*, which run parallel or nearly so to the dip;

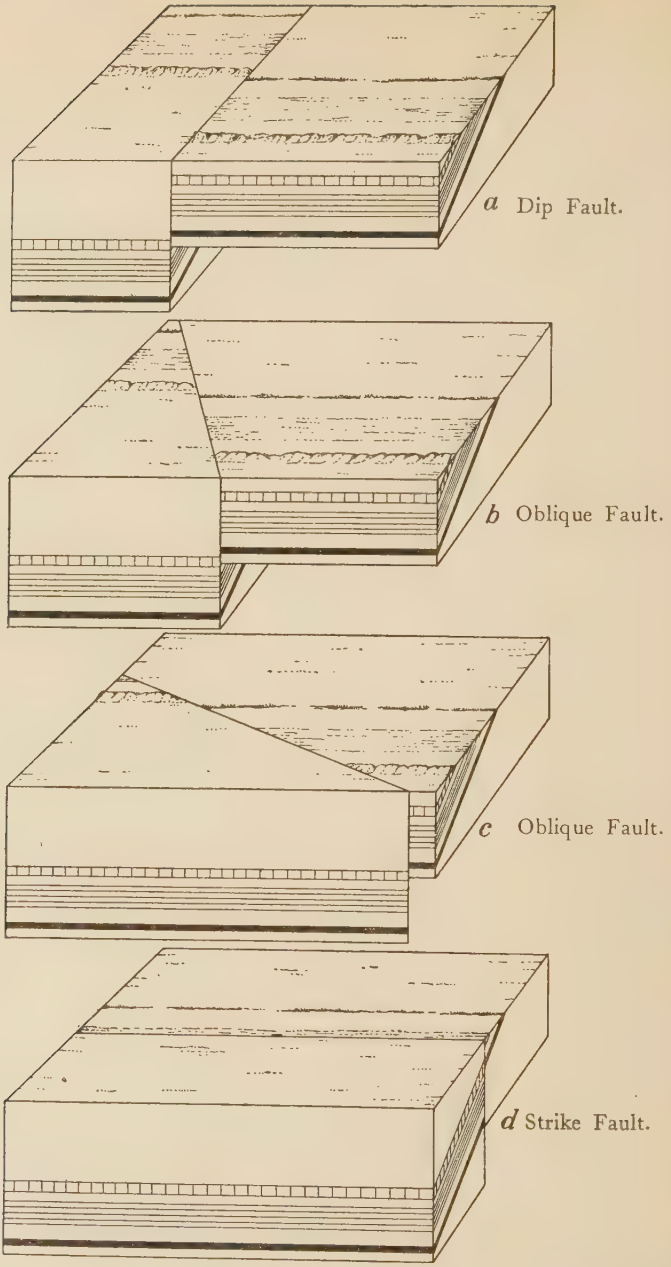


FIG. 48.—A SERIES OF DIAGRAMS SHOWING THE EFFECT OF FAULTING ON OUTCROP, WHEN THE DOWNTHROW IS DOWN THE DIP.

In (*a*) the beds outcrop as if they were shifted up dip on the downthrow side. In (*b*) there is a gap between the ends of the outcrops on either side of the fault, which increases with the obliquity as in (*c*). When the fault has veered round so far as to become a strike fault, several beds on the downthrow side are "cut out" and never reach the surface.

and *oblique faults*, which run in a direction between those extremes.

Further, the surface outcrop will depend on whether the downthrow side is on the up-dip or the down-dip side.

Take the case of a normal fault such as in Fig. 48 with the dip of the beds towards the observer. Three distinctive beds are represented: a younger limestone band, an older and thicker bed of shales and a still older seam of coal. The intermediate beds are left blank to simplify the diagram.

In Fig. 48 (*a*) the fault-plane is in the same direction as the dip of the beds, hence it is a true dip fault. On the surface one finds that the coal bed abuts against the younger shales, showing that the left-hand side is the downthrow side, as is the case in all the figures of the series. Fig. 48 (*b*) shows the fault changed in direction so that it is now an oblique fault though rather nearer the dip direction than the strike direction. The hade and downthrow remain the same, the downthrow side being with the dip of the rocks. Note that the surface appearance of the beds shows the same lateral shift of any one bed on either side of the fault, but that there is the beginning of a gap between the beds, so that it would be possible to walk in the dip direction and miss a bed altogether.

This apparent gap between the beds is increased as the obliqueness of the fault becomes more pronounced towards the direction of the strike as shown in Fig. 48 (*c*), and when it becomes a true strike fault as in Fig. 48 (*d*) one of the beds disappears altogether as far as surface outcrop is concerned.

Therefore in strike faults, which are commoner than dip faults, there will be a disappearance of beds on the surface when the downthrow is with the dip of the beds; but when the downthrow is against the dip of the beds as shown in Fig. 49 (*a*), (*b*), (*c*) and (*d*) there is an overlapping of the outcrops of the beds with an oblique fault and the échelon appearance becomes more pronounced as the line of the fault approaches the direction of strike. When the fault line coincides with the strike there is a complete repetition of certain beds close to the fault line.

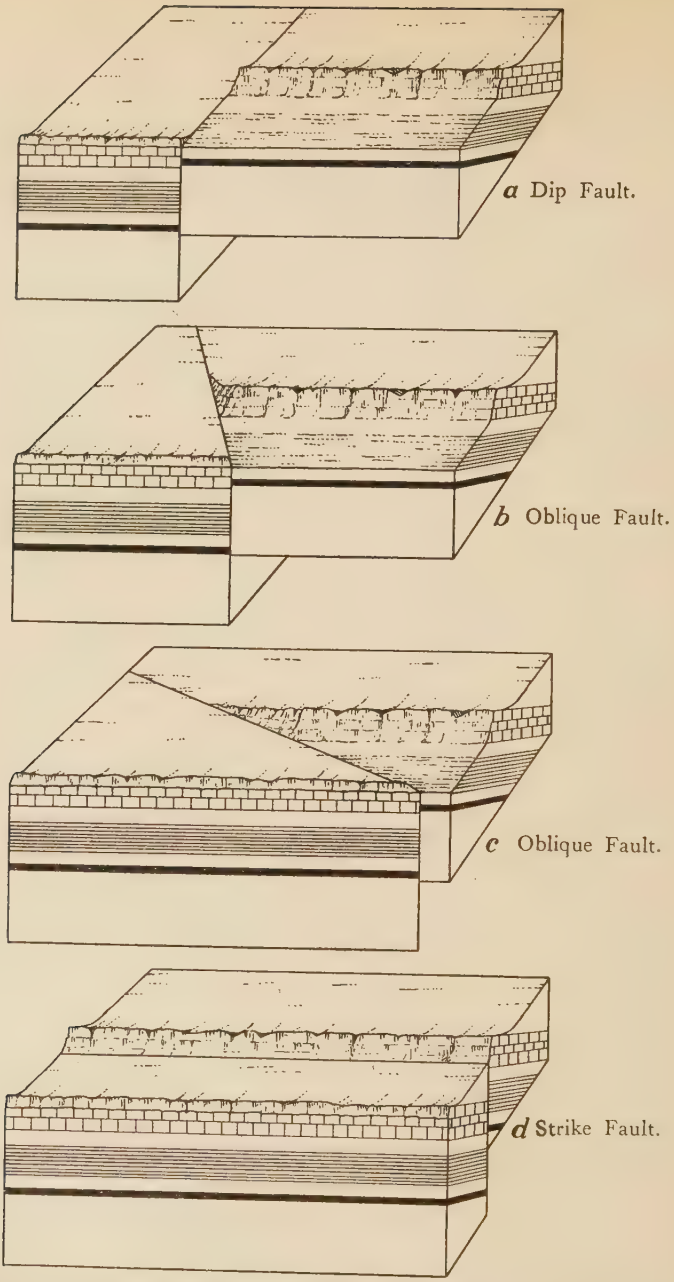


FIG. 49.—A SERIES OF DIAGRAMS SHOWING THE EFFECT OF FAULTING ON OUTCROP WHEN THE DOWNTHROW IS UP THE DIP.

On (*a*) the beds outcrop as if they were shifted up dip on the downthrow side. This case is similar to Fig. 48 (*a*). In (*b*) the beds are repeated for a short distance on either side of the fault, and this repetition increases in length with the obliquity of the fault, as in (*c*). When the fault has veered round so far as to become a strike fault, the repetition is complete.

It is possible, therefore, to frame rules as to the appearance of surface outcrops in normal faults, but it is better that beginners should not rely on hard and fast rules, to which there must always be exceptions, but should trust rather to graphic plotting of any particular case, or try to form a mental picture of the fault and its effect on outcrop.

One may now consider the field work of the geologist in connection with faults, and the kind of measurements he is called upon to make in order to determine the structure of a faulted area, treating at first of normal faults in strata of constant dip.

The direction of the fault plane across country is perhaps the first observation that should be made, once its existence has been determined.

It is clear that a measurement of first importance is the throw of the fault, for on that depends not only the depth of beds below the surface, but the heave or "barren ground," as it is called by miners, and also the amount of lateral shifting of the outcrop of beds.

The heave depends on the hade or inclination of the fault plane, so that if the hade and throw are known the heave can be determined.

With regard to the throw of a small fault one may be able to measure it with the greatest ease, as in a vertical section of the beds, or with some difficulty where only surface features are visible.

In a vertical section, it is, of course, necessary to identify the same bed on either side of the fault; this is not always easy to do and naturally quite impossible when the throw of the fault is greater than the depth of the section. With beds which have characters sufficiently marked to differentiate them the matter is easy, but with great thicknesses of shales it is often very difficult to pick out an "index" layer. What may not be apparent at a casual glance may show up when careful measurements are made between whatever variations there are in colour and texture, and the list for both sides of the fault compared. The sequence of thicknesses on either side may then give the clue which

can be confirmed by more detailed examination. Once the correlation of beds is made, the vertical distance between analogous beds can be measured either directly or by the indirect methods mentioned in Chapter III.

The heave and the hade of the fault can be measured also; but whether they will be the true hade and heave or only apparent, analogous to apparent dip, must depend on the direction of the vertical section with respect to the fault plane. In order to settle that point it is necessary to find the direction of the fault plane, and that cannot be done from a truly vertical section. On a more or less horizontal surface, on the other hand, while the direction of the fault may be apparent there is no direct evidence of the throw, hade or heave, which must be deduced from other measurements.

It can generally be settled which is the downthrow side of the fault, for on that side will be the younger rocks. In the case of a dip fault there will obviously be some relation between the displacement of the outcrops on the surface and the throw of the fault. Fig. 50 represents two blocks on either side of a fault plane which is vertical and runs from left to right. The fore block has been faulted down relative to the rear block. The broken lines on the rear block represent that part which has been removed by erosion: the dotted lines that part of the thin bed which has been removed with it.

If the rear block were lowered again to form once more the unfaulted and uneroded cube with the thin bed outcropping from front to rear, the vertical distance moved through would be the throw. Therefore, if the dip is known, the throw can be measured either by drawing a section to scale or by solving the triangle, for

Throw = horizontal displacement $\times$ tangent of the angle of dip.

It is assumed here that the surface of the ground is level: where it is not so, allowance must be made for the slope of the ground, and how to do this becomes clear when the section is plotted.

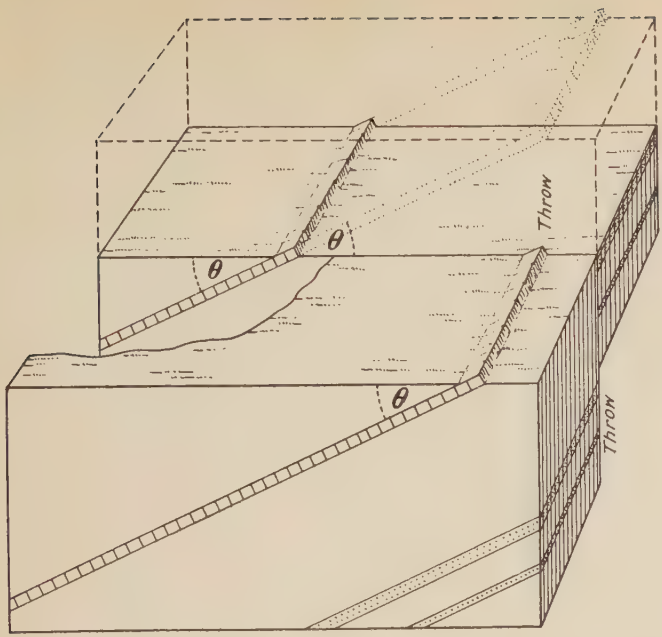


FIG. 50.—DIAGRAM OF A DIP-FAULT, TO SHOW THAT THE THROW CAN BE OBTAINED BY MEASURING THE HORIZONTAL DISPLACEMENT OF OUTCROP AND THE DIP.

The throw = horizontal displacement × tangent angle of dip.

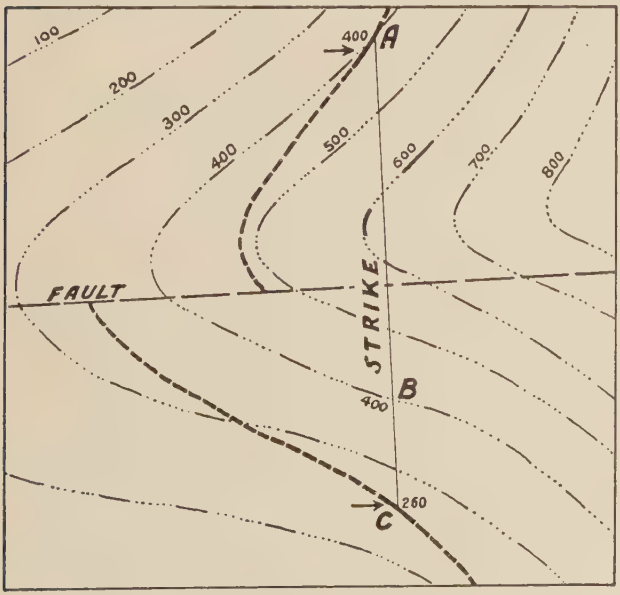


FIG. 51.—DETERMINATION OF THROW.

It will be noticed that the amount of surface displacement is not affected by the amount of hade of the fault plane. The dip of beds is not always constant, however, nor is it always easy to measure, and a method of calculating the throw from consideration of the strike is preferable where a contoured map is available or can be made for the area in question.

In the contoured diagram, Fig. 51, there is an outcrop of a bed at point A. A strike line through A, which will be at right angles to the fault since this is a dip fault, will reach the same contour on the other side of the hill at B. The bed does not outcrop at B, but, owing to the fault, at some other place such as C on another contour. Then the difference in height between B and C will be the amount of the throw since it is the vertical displacement due to the fault.

It must be noted here that when beds are dipping at a small angle, sometimes the slope of the ground in the direction of dip may be greater than the dip itself. In that case the displacement of the outcrop at the surface will be opposite in direction to what it is when the dip exceeds the slope.

There are many good examples of these combined effects of dip faults on the outcrops of beds, one of which is shown in Fig. 52, which illustrates well the difficulty of tracing faults over country of strong relief.

In the case of a strike fault it has already been seen that it is necessary to distinguish between one which has the downthrow against the dip and one which has it with the dip, the former case giving a repetition of outcrops on the surface and the latter cutting out some beds altogether from outcropping. In the former case the distance on the surface between the repeated outcrops will be apparently similar to the displacement of outcrops in dip faults, but there is an important distinction in that the amount of hade affects this displacement as well as the dip of the beds. This will be clear from Fig. 53, where AB represents the throw of the fault: the lateral displacement of

the outcrops is made up of the heave AC due to the hade, and CD due to the dip.

In a vertical fault plane, therefore, the method will give the throw, or if the hade is known the amount BC can be plotted or calculated: in practice it is often impossible

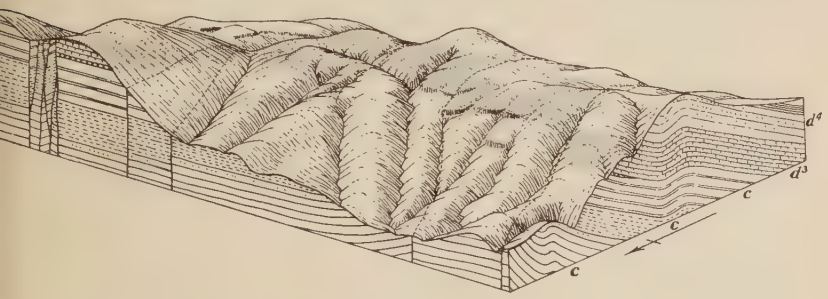


FIG. 52.—DIP FAULTING IN THE DIP MOUNTAIN, WEST OF LLANDILO, CARMARTHENSHIRE.

1-in. Sheet 230 N.S. Area shown, 14 sq. miles.

Carboniferous rocks resting on Old Red Sandstone, dipping to the south, are intersected by many faults trending north and south. In the part shown in the diagram, the downthrow is to the east at the eastern end, and to the west at the western end. Note the composite fault in the east. The effect of these faults is to shift the outcrops down or up the dip respectively. The carboniferous limestone is shown stippled on the land surface. The succession is:—d^4, Millstone Grit; d^3, Carboniferous Limestone; *c*, Members of the Old Red Sandstone.

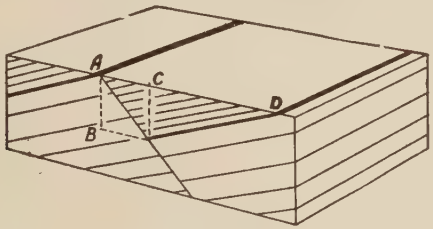


FIG. 53.—EFFECT OF HADE ON OUTCROP.

to find the hade of a fault, nor can one assume that when found it will be constant.

In the case of strike faults, therefore, one can get only an approximate value for the throw if the hade is known. In the latter case of the two mentioned above, instead of a repetition there is a section of the beds submerged, and it is the distance over which this absence of beds occurs which becomes the displacement. To measure such a

diminution of the outcrop involves a knowledge of the thickness of the beds and their sequence, which can only be had when the beds are very well marked and where they outcrop again somewhere in the vicinity. Consequently the determination of the amount of throw may frequently be a very difficult, if not an impossible, matter.

A good example of the surface repetition of beds due to a strike fault is represented in the block diagram of part of Carmarthen in Wales (Fig. 54), in which there are two faults both more or less in the direction of the strike of the Old Red Sandstone; consequently there are two sets of repetitions.

In the case of oblique faults the outcrop displacements will have the character of both dip faults and strike faults which are extremes of the general case. The nature of these displacements is fairly clear from Fig. 55, which illustrates examples of all cases.

As mentioned above there is often no direct indication of the existence of a fault and it is only suspected when there seems to be discontinuity in the outcrop of beds.

Unless the displacement is really clear, the only way to establish the position and nature of the fault is to trace the outcrops and plot them carefully and then deduce the fault from one's map. It is only with faults of small throw and clear surface indications that one can visualize the break in the field.

Having made all the observations in the field that are possible, one can best analyse the fault by drawing sections from the data obtained, the most useful direction for the sections usually being across the line of the fault itself.

When the main characters of the fault are established, a further set of observations in the field may clear up doubtful points.

It will be realized from the figures that the displacement of surface outcrops decreases with the amount of the dip, so that when the dip angle is small one may have to go a long way along the fault line to find the continuation of an outcrop. In the same way, if the slopes are steep

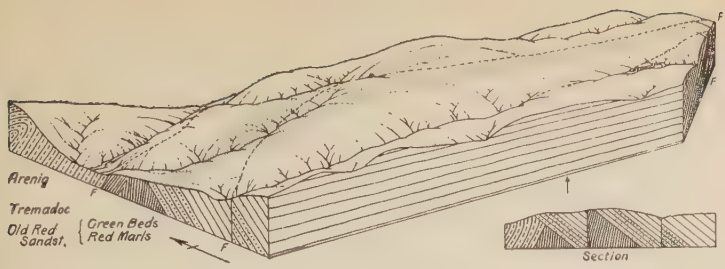
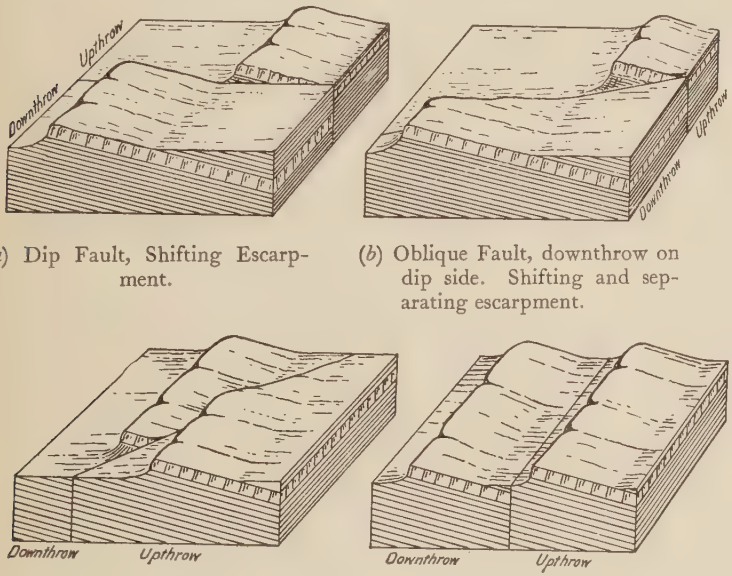


FIG. 54.—REPETITION OF BEDS BY STRIKE FAULTING. THE BLOCK REPRESENTS A TRACT OF COUNTRY IN THE SOUTH-WEST OF CARMARTHENSHIRE, WALES.

Sheet 229 N.S. Area shown, 7 sq. miles.

Cambrian and Ordovician strata are overlain with strong unconformity by Lower Red Sandstone strata which dip southwards. A large fault, which has a general direction west and west-south-west with downthrow against the dip, causes repetition. Another similar fault traceable only in the eastern end where it joins the main fault, causes a second repetition, as shown in the separate section. The probable course of this fault westward is marked by a small stream, the Nant Cwm ffrwd and at the western end it would join the main fault. These faults are Post Carboniferous. On the north Tetragraptus beds (Arenig) are overfolded against Upper Cambrian (Tremadoc).

Note.—Some Dip Faults on the north of the main east and west fault have been omitted for simplicity. Broken lines on the land surface are faults.



(*a*) Dip Fault, Shifting Escarpment.

(*b*) Oblique Fault, downthrow on dip side. Shifting and separating escarpment.

(*c*) Oblique Fault, downthrow against dip, shifting escarpment and bringing the ends *en échelon*.

(*d*) Strike Fault, repeating escarpment. An extreme case of (*c*).

FIG. 55.—THE EFFECTS OF FAULTS ON ESCARPMENTS.

and the dips are small the surface outcrops will be very tortuous and may even simulate the displacements due to the fault itself. It is clear then that under such conditions a topographical map of the area is essential.

When the beds have a steep dip, on the other hand, there is usually some folding present and that introduces a further factor to complicate the problem. There is one advantage in dealing with steeply dipping beds which are folded, and that is, that the succession of beds will appear on the surface several times and their sequence can therefore be studied away from the fault.

In economic geology the amount of the hade and of the heave may be of importance, and it may be worth while to make special borings to find them out. It is obvious that the hade of a fault is analogous to the dip of a stratum and is subject to the same kinds of deformation on an uneven surface. Therefore, if, on tracing the fault line, it is found to curve with or against the contours, an approximate measurement of the amount can be made.

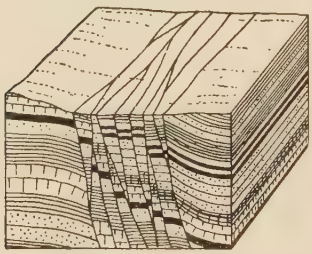


FIG. 56.—GROUP OF FAULTS.

In a district where there has been much faulting, a series of structures may arise which may be very puzzling indeed.

The faults may be in groups, as in Figs. 52 and 56, or, instead of a single fault of considerable throw, the surface rocks may have subsided in a series of faults of small individual throw. Such are known as step faults and their effect on surface outcrop is shown in Figs. 57 and 58.

Where a section of the surface beds has been let down with respect to those on either side, what is known as a trough fault is formed, which may be of any dimensions up to the land form known as a "rift valley." The converse to a trough fault is a "horst," where the sinking has taken place on either side of a block which has remained at its original level. This also may be of great dimensions.

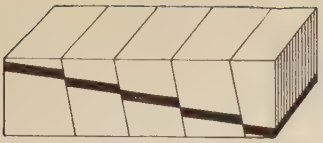


FIG. 57.—STEP FAULTS LEADING IN DIRECTION OF DIP.

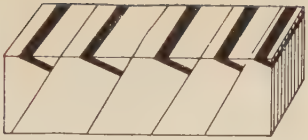
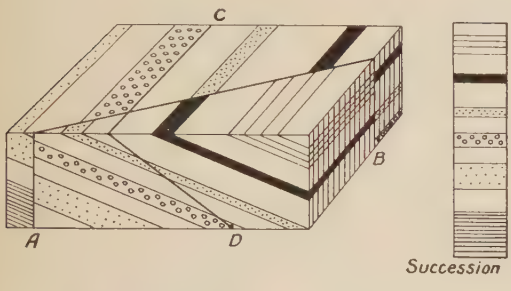
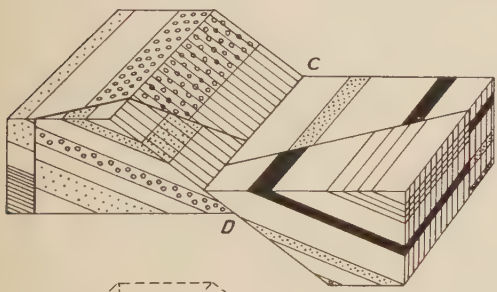


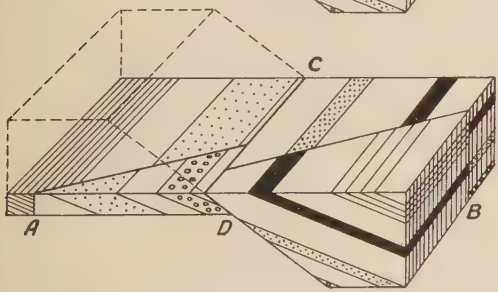
FIG. 58.—STEP FAULTS LEADING AGAINST THE DIP.



1. Block of Strata already faulted along AB, and outcrops shifted consequent on erosion to a uniform plane. Faulting imminent along the plane CD.



2. Faulting takes place along the plane CD parallel to the strike.



3. Denudation down to a uniform plane, showing shifting of the earlier fault AB.

FIG. 59.—COMPLEX OUTCROPS DUE TO TWO PERIODS OF FAULTING.

The strata at the sides of a horst often illustrate very well the connection between folds and faults, for the strata on the upthrow side are usually bent down and those on the downthrow side are bent up towards the fault. The same thing is likely to occur in any normal fault, and it is a fact to be remembered when measuring dips in the vicinity. A fault, in fact, very often turns into a monoclinal fold.

In a much disturbed area there are frequently two or more generations of faults crossing each other, rendering the surface outcrops very complicated indeed. Provided the lines can be traced, however, the relative ages of the faults can be determined, affording considerable help in the analysis of the faults. A diagrammatic example of such complexity is shown in Fig. 59.

Such faults cut up the surface into a series of polygons and the structure is known as Block Faulting. When in the case of block faulting or trough faulting the throw of the pair of faults is different in amount, there will be a tilting of the faulted block. This effect is well shown in the block diagram of the trough fault near Thirsk in Yorkshire (Fig. 60).

Reversed Faults and Overthrusts

Fractures of the strata of the earth's crust due to shrinking or compression must now be considered. When the stress acting upon the surface crust is of this nature, the movement of the beds when broken will be such as to reduce the area occupied, the beds one side of the break being pushed up relatively to those on the other side.

This phenomenon is known as a reversed fault, the simpler forms of which are at first sight similar to normal faults (see Figs. 61 and 62). The differences are important, however, and must be considered fully, if such occurrences in the field are to be recognized.

It has been seen that a fault caused by tension and downthrow of one side may be vertical or may have a slight inclination (hade) to the vertical. But a fault due to lateral thrust obviously cannot be vertical, and its hade is likely

to be much more extreme than in the case of a normal fault. In other words, the inclination of the fault plane will tend to be great and the direction of the hade will always be towards the upthrow side.

Again, in the case of a normal fault the movement of one set of beds over another may cause a certain amount of disruption of the edges of these beds, causing their

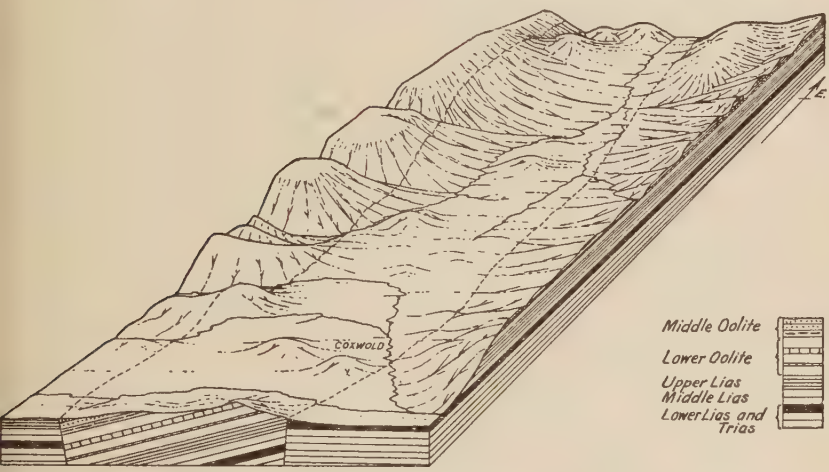


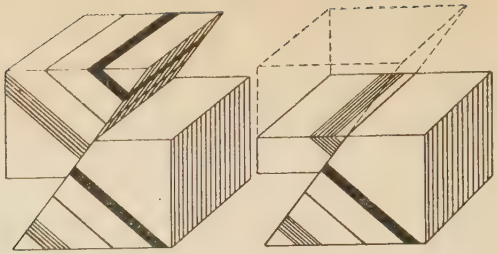
FIG. 60.—TROUGH FAULT IN THE NEIGHBOURHOOD OF THIRSK, YORKSHIRE.

Sheets 52 and 53 N.S. Area shown, 16 sq. miles.

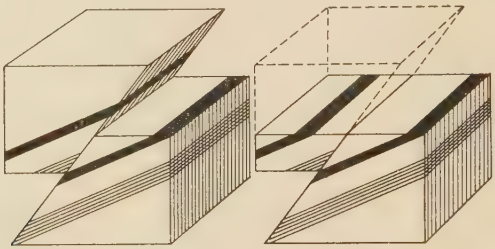
The two boundary faults run east and west, being traceable from near Ripon to Nunnington on the east, a distance of 24 miles. They maintain a distance apart of from ½ to 1½ miles. Their effect is to preserve a belt of younger rocks between older ones.

The diagram represents 6 miles of the trough towards the eastern end. In the far distance and middle distance Kimmeridge Clay outcrops with Middle and Lower Oolites on either side. A prominent fault scarp is seen on the northern side.

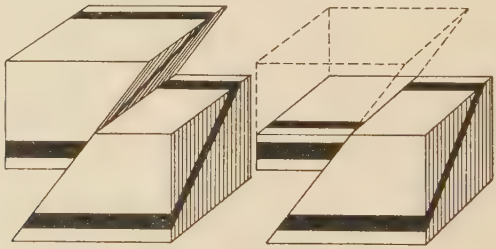
bending up or down on the downthrow and upthrow side respectively. But since the force responsible for such a fault is tensional, this disruption cannot be very great. In the case where one set of beds is being pushed against the other, however, as in a reversed fault, the bending and breaking of the edges is likely to be much more intense and often leads to the formation of a strip of much broken material on either side of the fault plane. This is variously known as a fault-breccia or a crush-breccia, or if very wide-



(*a*) Strike Fault. Downthrow in the direction of dip, or hade against dip. *Cutting out* of beds.

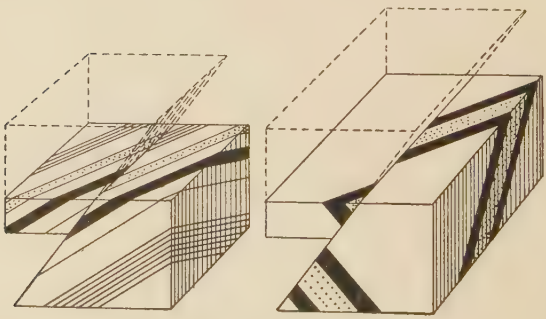


(*b*) Strike Fault. Downthrow against the direction of dip and hade with dip. *Repetition* of beds.



(*c*) Dip Fault. Shifting of Outcrop.

FIG. 61.—DIAGRAM OF REVERSED FAULTS.



(*a*) Downthrow against direction of dip. Echeloned beds with partial repetition.

(*b*) Downthrow in the direction of dip. Echeloned beds with a gap.

FIG. 62.—OBLIQUE REVERSED FAULTS.

spread it may be called a shatter-zone. Where the masses and forces involved are very great, this breccia may be so distinctive in character as to simulate a different kind of rock altogether.

With reversed faults the actual effect on the displacement of surface outcrops will naturally be the same as in the case of normal faults, since, so far as vertical displacement of beds is concerned, merely one side of a fault is pushed up instead of being dropped down. Fig. 61 shows diagrammatically that dip-faults and strike-faults have precisely the same effect on the surface and outcrop that the downthrow side of the fault always has, the younger beds outcropping at the line of the fault.

Since it is compression which is the cause of reversed faults, they are naturally much more closely connected with folding than are normal faults, and it is rare to find a reversed fault occurring in strata which are nearly horizontal. The connection between a reversed fault and a fold is very often actually a genetic one, as is shown in Figs. 36 and 37, where the increasingly acute overfold stretches the beds in the limb between the anticline and the syncline until these beds give way altogether under the tension so that a fault is caused along a limb. It is interesting to note that this structure on a miniature scale is very common in highly contorted rocks, especially where a softer band is intercalated between harder ones.

In a case where the strata have given way to the compressional forces by, not only one, but a series of reversed faults, what is known as imbricate structure arises, as shown in Fig. 64, a phenomenon which is somewhat analogous to the step-faulting in the case of tensional faults.

When the hade of the fault plane is considerable, so that the movement of the strata is more horizontal than vertical (as in the case of the recumbent fold in Fig. 37 which has become a fault), the fault is known as an overthrust and the fault-plane is then called a thrust-plane. Overthrusts are a very important feature of mountain building,

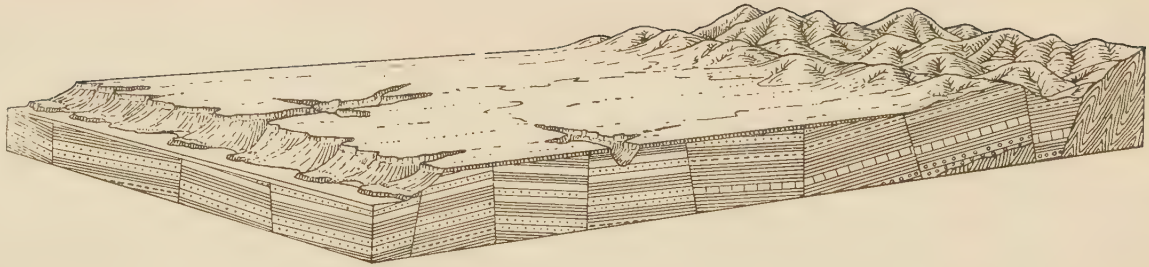


Fig. 63.—Block Faulting, Mancora, N.W. Peru.

Tertiaries are strongly developed along the Peruvian littoral and reach a thickness of at least 25,000 feet. The sea has advanced and receded several times since the faults were formed and has left a number of floors with beaches. The most striking floor is known as the Mancora Tablazo, which has an elevation of 1,100 feet, and a thickness of nearly 300 feet in this part of the country. Deep canyons have excavated through this floor and the drainage has thus been superimposed on the Tertiaries. In the hinterland the Amotape Mountains rise to a height of over 4,000 feet: they are composed of slates and quartzites of undetermined age, Carboniferous shales, and some Cretaceous limestones and shales.

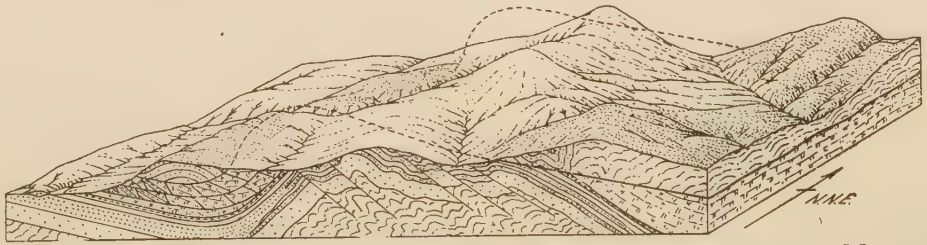


Fig. 64.—The Ben More Thrust Plane in the neighbourhood of Beinn an Fhurarain, Assynt Mountains, N.W. Highlands of Scotland.

1-in. N.S. Sheet. Area shown, 12 sq. miles.

A sheet of Torridonian Sandstone and Lewisian Gneiss has been thrust over Cambrian rocks, giving rise to imbricate structure. Denudation of the sheet has led to the formation of outliers (Klippen).

but the difficulty of analysing them is considerable, and it is only in comparatively recent years that their frequent occurrence has been fully accepted. In the large overthrusts of the North-West Highlands of Scotland or of the Alps of Switzerland, for instance, the actual horizontal movement of vast sheets of rock has been shown to extend to many miles; only the most careful geological surveying can elucidate such complicated structures, and even then they are often open to more than one explanation. Such work is perhaps the most difficult that a field geologist can be called upon to do, and it is not necessary to do more than allude to the kind of structures produced by such wholesale movements of translation.

In the simplest case of an overthrust the moving mass may be left comparatively undisturbed except at its front, where it is liable to be overfolded. The mass over which it moves will be affected in a degree proportional to the amount of frictional resistance which it offers. In some cases there may be no greater result than a shatter-zone below the moving mass. In other cases the underlying mass may be rent by a series of reversed faults giving the structure which has just been alluded to as imbricate. In a less simple case there may be a considerable degree of overfolding, giving rise to the complication in the field of a succession of beds being inverted so that the older beds rest upon the younger. This may happen before there is any translation movement. Again, the overthrust may take place along one plane until it reaches a degree of stability or of resistance sufficient to check further movement along that plane, after which a new thrust-plane may be formed. Frequently there are a series of minor thrust-planes along the weaker beds, the sole of the thrust-plane being itself folded to some extent. Further, there will occasionally be relative movements of one fold over another, which, though due to the same general forces as the overthrust, may be conveniently styled "slides." One of the commonest effects of overthrusts will be that older rocks are found resting on younger rocks, a fact due

not only to inversion of beds but to a bodily movement of the older over the younger. When erosion has taken place, the more resistant rocks may be quite cut off from their original stock, giving rise to a mass, usually a mountain, without "roots." The Matterhorn of the Alps is a classic instance of a mountain without roots, it having formed part of a travelled rock-sheet or "nappe" which has come from Lombardy, over 30 miles away.

CHAPTER VII

THE STRUCTURE OF IGNEOUS ROCK MASSES

WITHOUT going deeply into the origin of igneous rocks one realizes that they cannot possess the comparative simplicity of structure which is found in the case of stratified rocks which are originated by sedimentation processes. Nevertheless, there are certain characteristic shapes of igneous masses which it is important to recognize in the field, especially as some of these shapes simulate those of sedimentary deposits in a remarkable degree.

Igneous rocks have all at one time or another been in a fluid state, but they may have solidified deep down in the earth's crust, or just beneath the surface, or on the surface itself as a lava. Such a division of these rocks into plutonic, hypabyssal, and volcanic is a useful one, since the texture of the rock depends to some extent upon the time which it took to solidify. Consequently fine-grained rocks are likely to be volcanic, coarse-grained plutonic.

The ordinary processes of denudation will in course of time expose even the deep-seated plutonics, so that a boundary line between it and the surrounding rocks may be followed and a plan of the boundary may be surveyed in the ordinary way. Vertical sections of such occurrences are less common, but sufficient is known of their shape for one to be able to classify them into two main types; (1) the Bathylith, and (2) the Laccolith. The former is usually a shapeless mass of large dimensions which gives the impression that its size increases still more with depth. The laccolith, on the other hand, is smaller and appears to be a local expansion of a parent magma, along bedding

planes, to which it is connected by a pipe of the same material, smaller in section than the laccolith itself. The general appearance of these two types is shown in Figs. 65 and 66. It will be seen, therefore, that to survey an occurrence of igneous rock of massive type, one can take nothing for granted, but must follow round the visible boundaries as best one may. For although it is usually of rounded outline in plan, there may be projections and re-entrants which follow no obvious plan. Sometimes, however, the mass is elongated in plan and it may be possible to correlate this elongation with the axes of folding of the area. Fortunately, the tracing of the boundary is not usually a very difficult matter, since the superficial appearance of the igneous rock is different from that of the sedimentary rocks into which it has been intruded. But when the rocks surrounding the igneous mass are of great age and have been much metamorphosed so that they have lost their own structure, it is not always easy to determine the exact boundary. Furthermore, the igneous mass often fuses, and dissolves some of the surrounding rock, so that a selvage of hybrid rock which is neither wholly igneous nor wholly sedimentary may surround the whole bathylith. In some cases the igneous mass has extensions which may form comparatively narrow sheets, but in the plutonic rocks these are rare.

When the denudation over an igneous mass has not gone far enough to remove all the superimposed rocks there will not be a simple boundary between the invaded rock and the intrusive, but there will be patches of the one apparently surrounded by the other as seen in plan.

These isolated masses may be of large or small size and the mapping of their boundaries may be a long task. It is an important one, nevertheless, if the true state of affairs beneath the surface is to be elucidated. For if one finds a patch of sedimentary rock surrounded by a granite the occurrence is open to at least three interpretations. As shown in Fig. 69 it may be due to the granite having flowed round a portion of the sedimentaries which still

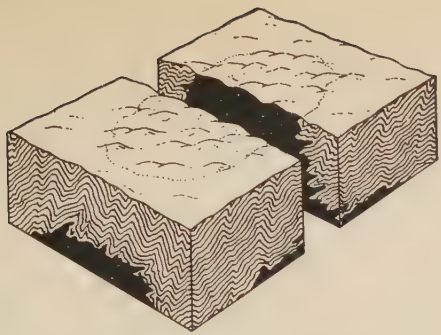
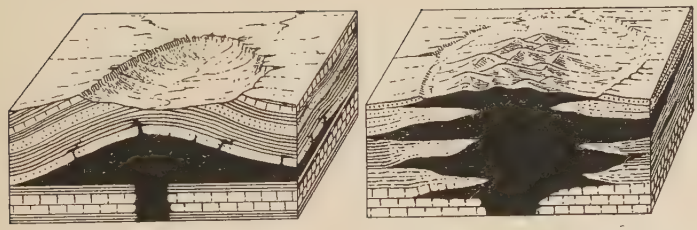


Fig. 65.—Bathylith.



(*a*) Laccolith. (*b*) Cedar-Tree Laccolith.

Fig. 66.

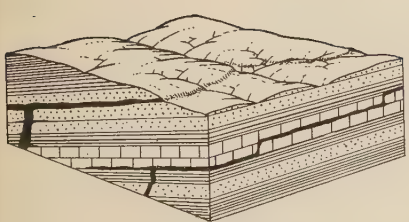


Fig. 67.—Sills.

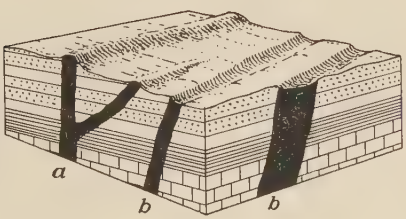


Fig. 68.—Dykes.

(*a*) Of more resistant material, (*b*) Of less resistant, to weathering, than the country rock.

remains attached to its main mass below the surface, as in (*a*). Or it may be a residual of the sedimentaries left by the denudation in a pocket on the granite, as in (*b*). Or finally it may be a giant inclusion of the sedimentaries

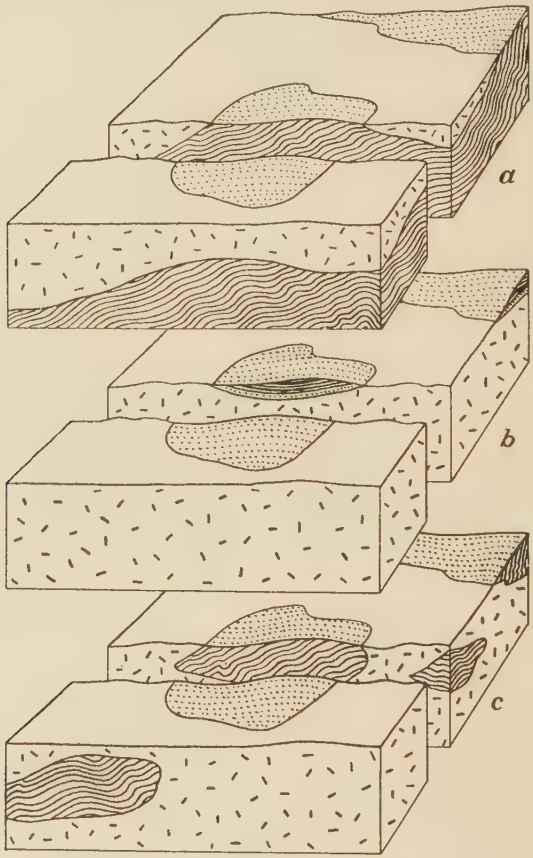


FIG. 69.—TO SHOW HOW SIMILAR OUTCROPS CAN ARISE FROM QUITE DIFFERENT STRUCTURES.

Igneous: broken lines in section, unmarked in outcrop.
Stratified Rocks: continuous lines in section, dotted in outcrop.

which has been lifted up when the granite intrusion took place and in fact was then floating in the molten mass.

It is clearly of importance to establish which of these explanations is the correct one. The petrographical evidence, such as the texture of the granite close to the

junction, and the amount of metamorphism the sedimentary rocks have undergone, may be of great assistance in settling the question, but it must be backed up by careful mapping of the boundaries of each exposure, of the dip and strike of the sedimentaries and of the surface relief.

It is clear from its form that a laccolith cannot readily be recognized as such from a surface outcrop, but, being intruded nearer the surface and therefore under less pressure, it is frequently found to have more extensions in the form of penetrations into the surrounding rocks than the true bathylith.

The effect on the superincumbent strata is usually more apparent than in the case of the very large intrusions, the surface being raised into a low dome, with the strata dipping outwards from the centre. The classic instances of this structure are in the Henry Mountains of the state of Utah, described long ago by G. K. Gilbert. In this case it seems clear that the force of the igneous mass caused the dome structure, but in others it is possible to consider that the folding was antecedent to the intrusion of the igneous rock, which thus found an area of weakness for its penetration.

But since a dome of circular section cannot be caused by any ordinary crustal compression, one may confine any suspicion one may have to those cases where the laccolith is definitely elongated in plan and occupying a pitching anticline, a form of folding which can be caused by lateral compression.

A laccolith is, in fact, something between the large bathylith and the comparatively small masses of eruptive rock which are found in sheets penetrating sedimentary rocks. If these sheets are interleaved between the strata, they are known as sills; if they cut across the bedding, they are known as dykes or veins. Thus a sill may become a dyke for part of its course. Of these two forms the sill is the more important, for it not only simulates the appearances of a sedimentary rock, but if, as is often the case, it is very much harder or softer than the strata above and

below, it usually has a dominant effect upon the land forms of the area. Such sills may be of any thickness from a few inches up to hundreds of feet, with a texture varying from fine-grained at the upper and lower edges where it is cooled rapidly to coarse-grained in the centre. Very frequently, too, the contraction on cooling induces a columnar structure of rough hexagons whose axes are perpendicular to the plane of cooling contact. Usually sedimentary strata intruded by the sill are altered for a few feet from the junction, and occasionally there are signs of the vertical movement of the strata in the form of fractures, massive inclusions of the sedimentaries in the eruptive rock, monoclinal folds and so forth. Clearly the intrusive rock has followed the line of least resistance, and for that reason it is very often found at the same horizon in the sedimentary strata over a wide area; but it obviously will not do to take this for granted, since the molten rock may find an easier path across the bedding and through it rise to a higher horizon. In level-bedded strata, on the other hand, the structure is such that, given an extruding force impelling the molten rock upwards, it is often easier for this to spread out as a sill than to break vertically through to the surface as a dyke. Under suitable conditions, the area which can be occupied by such a sill is truly remarkable; on the Antarctic continent, for instance, there is a series of sills which appear to stretch for nearly a thousand miles, though it is probable that they arise from a number of magmas rather than from one. From the foregoing it should be clear that the mapping of such an occurrence is comparatively simple where the sill is of uniform thickness and has kept to one horizon, but one must not assume that this is so over wider areas.

Should the igneous rock find an outlet up to or towards the surface, its shape will usually be either that of a pipe or neck or else a thin vertical sheet, a dyke. These, when laid bare by erosion, are comparatively easy to recognize and to map. They are not commonly of large size, and dykes, for instance, are rarely continuous across

country for any very great distance, though there are some interesting exceptions to this general statement.

Igneous dykes exhibit a very great variety of type and structure and may be regarded as features of great assistance in the field towards the elucidation of the igneous geology.

In a general way they may be classified into regional and local series, although one division merges into the other. The local type may often be traced to the parent mass or at all events to a central zone above that mass, in which case there may be little relation between the structure of the rocks penetrated and the direction of the dykes.

In the regional type, on the other hand, the connection with a parent mass is usually not apparent, but a marked parallelism between the dykes denotes that they occupy lines of weakness due to tectonic strain at the period of their intrusion. In either case it is naturally important to establish the general direction of the dykes.

The actual dimensions of the dykes are of less importance, but they should be noticed in a general way and the occurrence of extensions and apophyses should be plotted. Very often a series of dykes may contain sets of more than one age, as shown by one set's intersecting another, and the network produced may, when plotted on the map, give the clue to their respective ages.

When a dyke traverses an igneous mass such as a granite it may be the only indicator as to the age of the granite.

Enough has been said, perhaps, to show that a dyke or igneous vein requires very careful examination, even apart from its petrographical evidence, and that its direction should always be noted.

If the rock is in the form of a neck it is usually harder than the surrounding rock and will form a more or less rounded hill, of striking appearance. Occasionally, however, the eruptive rock may be more subject to surface erosion and the effect of solution by water than the surrounding rock, in which case it will form a basin instead of a hill.

Surface lavas are the last form in which igneous rocks can be found, and the first point to determine is that they are surface lavas and not sills. This is, usually, a fairly simple matter, since any sediments deposited upon a surface lava will be unaltered, and will also follow the sinuosities of its surface. Moreover, a surface lava will nearly always betray itself by its vesicular habit.

Apart from the actual shape of igneous rocks, it may be important to determine their age. Obviously the ordinary law of superposition, that is to say, that younger rocks are laid down on top of the older, will only apply

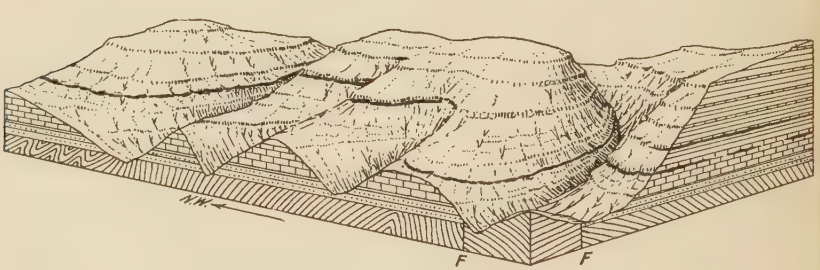


FIG. 70.—INTRUSIVE SILLS IN THE CARBONIFEROUS LIMESTONE, MURTON FELL, DURHAM.

Sheet 31 N.S. Area shown, 8 sq. miles.

Note the sills at different horizons, their vertical transgression of beds and lateral discontinuity. FF is a fault across the corner of the block. The floor is of Lower Silurian Rocks.

in the case of surface lavas, and the age of any other form of igneous rock must be deduced from other evidence; thus, though a sill is obviously younger than the rocks it intrudes, one cannot say for certain how much younger it is, unless one finds beds of known age lying unconformably upon these rocks and containing rolled fragments of the sill material.

There is still another type of rock, which being igneous in composition yet sedimentary in structure, may be difficult to classify in the field. The ejectamenta of volcanoes are laid down in beds which become more evenly stratified the further away they are from the centre of eruption, and, especially if laid down under water, these beds are, in

structure, exactly similar to the ordinary products of erosion and deposition. These volcanic tuffs are, in fact, sedimentary rocks, but since their origin is catastrophic rather than seasonal, they have a story to tell which is very different from that of the ordinary sedimentaries. An interesting case of the sub-aerial deposition of volcanic débris is to be seen around Cotopaxi in Ecuador. A thick blanket, composed of layers of ash and pumice separated by thin peat beds, lies evenly over the country for many miles from the cone of the volcano, which is active. The bedding planes conform exactly with the present topographic undulations, curving over spurs and dipping down valleys. The only exceptions are where small ravines have been excavated into the blanket. The layers of ashes and pumice, light yellow in colour, are from a few inches to several feet in thickness: the partings of peat generally are only a few inches thick. The former represent outpourings during periods of activity: the latter, accumulation of decaying vegetation during periods of rest.

A good deal of the evidence is purely petrographical and beyond the scope of this book, but it should be obvious that such structures are worth close investigation. Thus the presence of larger material mixed with the finer, the occurrence of false bedding and the association of the tuffs with lavas are all presumptive evidence of the proximity of the centre of eruption.

Even when laid down far from this centre as fine-grained muds the thickness of the laminæ and the proportion of true volcanic to true erosion material denote roughly the periods of successive eruptions and the conditions of the sea when the tuffs were laid down.

It is not unusual, for instance, to find that volcanic tuffs of this kind are more prolific of fossils than other beds, for obvious reasons.

On the other hand the thickness of such beds is no guide to the time taken for their formation, although, if they can be followed away from the eruption centre to where they begin to thin out and become interleaved with

ordinary stratified deposits, the correlation may lead to very important conclusions.

It will be seen from the foregoing that the field work connected with the mapping and examination of igneous rocks is less susceptible of method than is the case with sedimentaries. On occasion, however, it may be just as important, especially in economic geology.

One may sum up the matter as far as structure is concerned by saying that the field observations should if possible determine, first, what category the igneous mass falls into, by a survey of its boundaries, and, second, its approximate age.

In general, however, the full character of eruptive rocks is determined more from petrographic evidence than from their form and structure.

CHAPTER VIII

SURFACE RELIEF

THE early British geologists laid down what was known as the Doctrine of Uniformity, which states that on the whole the processes which were responsible for the formation of rocks in the past are the same as those which are now at work upon the earth's surface. Nothing has since been discovered to disturb the general acceptance of this doctrine, and it is therefore important that the geologist should give some time to the study of these present-day processes if he is to interpret successfully the record of the rocks.

The study of surface land forms, sometimes known as geomorphology, has become a branch of present-day geology; and although the subject is too vast for thorough treatment here, an attempt will be made to describe some of the more typical land forms, their connection with the rocks from which they are shaped, and their value as accessory evidence to the field geologist.

Very little space can be allotted to the processes by which surface relief is moulded, but one may remind the reader of a few ruling factors which are treated fully in textbooks on geology and geomorphology. For the sake of simplicity denudation and deposition processes may be regarded as coming under two headings only: first, those due to sub-aerial agencies such as wind, frost, ice, and, above all, running water; and, second, those which are due to marine action, chiefly, of course, at or near the shore line. These two agents are responsible for the universal degrading of the surface of the land and the laying down of the material in fresh beds, most of which in their turn will become

more or less consolidated rocks. The sub-aerial processes are familiar to all, and it is perhaps convenient to consider them as divided into two classes, first, those responsible for what are usually called the weathering of the surface; and, second, those which actively erode, the erosion usually implying transport as well, since without removal of the waste there must be a stagnation of the process. The actual nature of the different weathering processes must be here taken for granted: but it is of some importance to consider the characteristics of water erosion by rivers and streams before passing on to the different types of land form produced thereby.

A river, in its course from the uplands, where it first becomes a running stream, to the base level—whether lake

Fig. 71.—Erosion Curve.

or sea—passes through a series of stages which vary markedly in the amount and kind of effect which characterize them (Fig. 71). The summit of a watershed, below the snow line and under the influence of rain, is usually convex and somewhat rounded in form, being subject to weathering processes, the products of which are not removed completely, since the amount of running water is not sufficient. But further down the slope where definite streams arise there begins a long curve known as the curve of erosion, which takes the form of a logarithmic curve, its gradient decreasing from source to base level. This curve is caused by the work of erosion varying at different stages along the river's course. The work done by a river depends, amongst other things, upon its volume and rate of flow, the latter depending chiefly upon the

gradient of its course. Further, the erosive power of the running water will depend upon the amount of solid material in suspension, and to some extent upon the nature of that material. It is seen, therefore, that the rate at which a river will degrade its bed depends upon a number of factors, some of which are common to all rivers. Thus, at and near its source, the river, though it has a maximum gradient, has a minimum volume and therefore carries a minimum amount of load with which to corrade.[1] As it progresses down the curve of erosion the volume will be steadily increasing and the gradient decreasing. The load will also at first increase. Consequently there is a zone where erosion will be at a maximum, for above that zone, though the rate of flow is higher, the volume and eroding material is less, while below that zone the greater volume of water does not make up for the slower rate of flow due to the slighter gradient. A corollary to this latter statement is that the river will begin to deposit, as well as erode, in its lower reaches, and finally, where base level is almost reached, deposition will almost entirely replace erosion. The normal river, therefore, flowing over more or less homogeneous rocks, will have the characteristics shown in Fig. 71. If the bed of the river is formed of rocks of different resistance to erosion there will be temporary modifications of the curve of erosion.

The beginner is apt to be sceptical as to the amount of erosion of which a river is capable unless he sees it in full flood, when it becomes apparent that nearly all the work done by it in changing its bed downwards or sideways is done during the short periods of flood.

This is a very important fact and cannot be fully comprehended unless the mechanics of the motion of water receives some attention. For instance, the power of

[1] The word "erosion" is often taken to imply denudation both by solution and by mechanical means, the word "corrasion" being reserved for the latter alone. It is important to note that corrasion may be lateral as well as vertical, the former continuing to take place in the lower reaches of a river when all vertical corrasion has ceased.

running water to carry pebbles of different sizes obviously depends upon its velocity, but it is somewhat surprising to find that this capacity is proportional to the 6th power of the velocity.

Thus, if a river at a given velocity can just move a pebble of a given size (volume), if the velocity is doubled it can move similar pebbles of 64 times the size of the first pebble.

The matter is further complicated by the fact that water loaded with sediment has a greater effective density than clean water and therefore can support heavier pebbles. The theoretical study of the relation of "load" to velocity has not been fully supplemented by practical experiment, but enough has been said to show why it is the river in flood rather than the river at normal times which changes the land forms.

So much for the section along a river bed, it being understood that the sections along tributaries are of the same general character, though in that case the main stream may be regarded as a sort of temporary base level for the tributary.

The plan of a river system, though normally to be likened to a tree with its trunk and branches, exhibits many variations from that simple pattern. In observing the effect of a sharp shower of rain upon a low pile of clay or silt, illustrated in Fig. 72, the stages of a river system in miniature can be followed. At first there is a myriad of small streamlets following the general slope of the pile and "consequent" upon that slope. But, owing to accidents of the surface, some of the streams grow in volume faster than others and therefore lower their beds more rapidly. Some of the minor streams are then absorbed by the larger and others are diverted so as to form tributaries to the larger. The direction of these tributaries is then not along the original slope but along the new slopes formed by the main stream.

The process continuing, the longer streamlets grow at the expense of the smaller, until there are left a few main

water courses running in the original consequent direction, and many tributary, subsequent, water courses joining the main ones at an angle which is usually considerably less than a right angle. Should the pile be composed of material which varies in its resistance to the flow of the streamlets, one would find the plan of the stream modified considerably.

Thus a large stone in the pile would divert a stream so that it had to desert its "consequent" direction for some distance, while a harder band of material at right angles

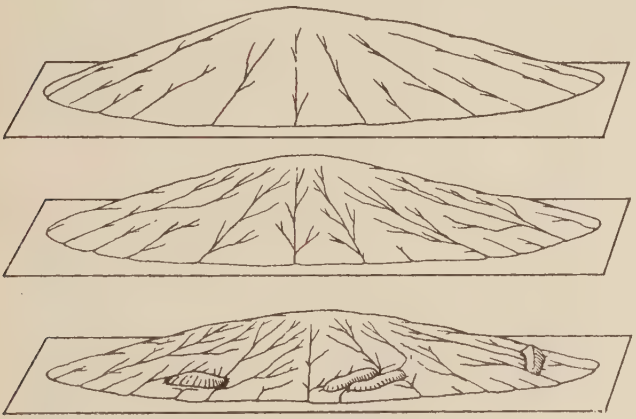


FIG. 72.—GROWTH OF STREAMS.

to the slope would tend to encourage "subsequent" streams which would come into the main one at right angles, and so on.

If, instead of the pile of clay, a comparatively large area of land is considered, the boulder being replaced by a mass of hard igneous rock, and the hard band by a series of harder beds of rock, one would see the same thing happening on a large scale, though an immeasurably longer time is required to produce the same kind of results. In nature an exact parallel to the example of the pile of clay is rarely found, although something like it occurs when freshly deposited masses of volcanic ashes and dust are attacked by weathering agents.

The same thing should occur when a section of the

sea bottom is raised above sea level, but the process of emergence is usually a very slow one and the surface only gradually comes under the full action of sub-aerial erosion.

Nevertheless, it should be clear that the direction of any stream and, consequently, the plan of a river system, depends, first, upon the direction of slope, and, second, on the kind of material it is flowing over. It also depends on the time during which erosion has been going on, since there is a good deal of absorption of weak rivers by strong (river capture) and consequent shifting of divides which alters the plan.

Many of these changes follow fairly well-defined laws which are stated and elaborated in treatises on geomorphology, and these laws also provide bases of classification of land forms.

The best accepted classification is based upon the duration of time during which erosion processes have been acting on an area, or, more accurately, upon the stages in a complete cycle of changes of the surface due to these processes unhindered by earth movements. This is known as the "cycle of erosion," and although there are no clear examples of such a completed cycle over a large area, since crustal movements usually interfere with the ordered course of the changes, it is a very useful concept: it is possible to recognize different stages in the ideal cycle and to classify areas in that way. The complete cycle may be considered as commencing with the emergence above sea level of a more or less regular surface of land. If, then, the manifold agents of degradation are allowed free play, the various stages in the alteration of the land forms will be somewhat as represented in Fig. 73.

The rain which falls on the surface will at first run off in a myriad consequent channels or will collect in the low basins and form temporary lakes, but towards the edge of the land where the velocity of the streams is greatest they will cut down their beds at a rapid rate and form narrow V-shaped valleys.

This is the stage of extreme youth in the cycle and is

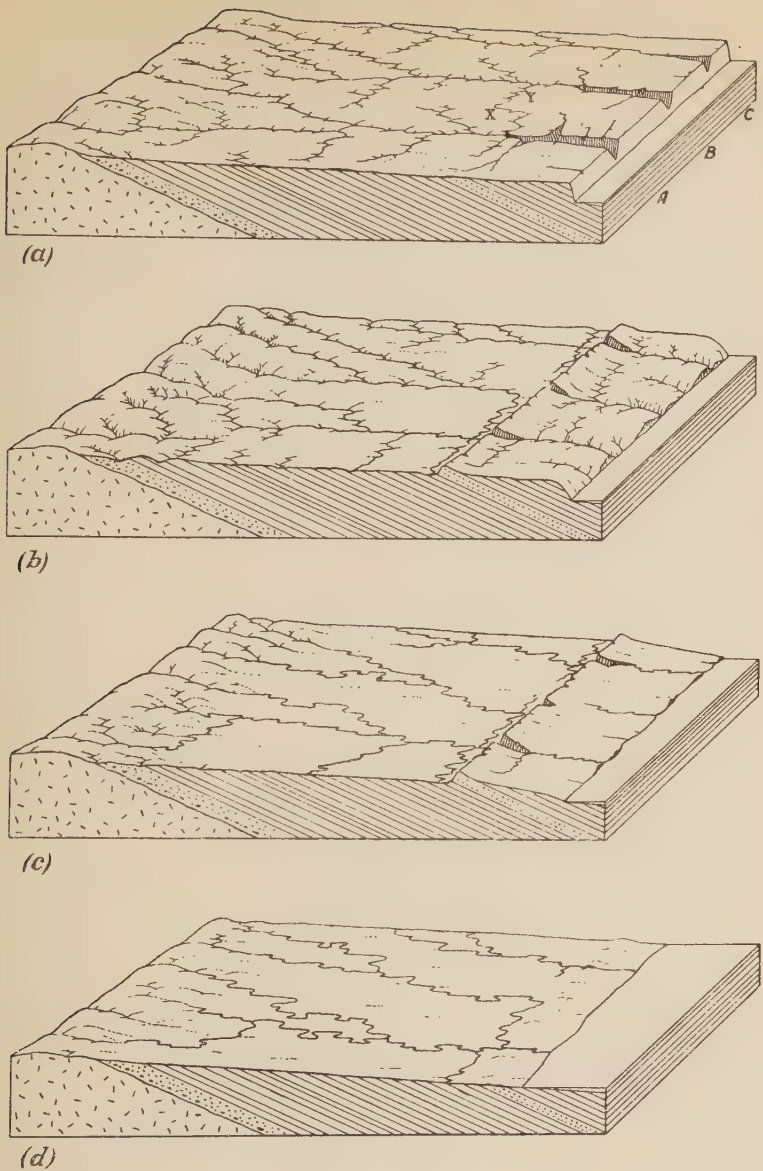


FIG. 73.—CYCLE OF EROSION.

(*a*) Youthful stage, (*b*) Sub-mature, (*c*) Mature, (*d*) Senile.

It should be noted in (*a*) that, since the stream A has a greater drainage area than B or C, it has cut down its V-shaped valley to a lower level. Owing to this greater depth of valley its tributary X has a steeper gradient and therefore more erosive power than the tributary Y of stream B, with the result that X will cut back its watershed until it taps the main stream B and capture it, as shown in (*b*).

marked by contrast between the older level plain and the young steep-sided valleys.

At a slightly later stage the rivers will have begun to seek out the softer beds and to work back farther and to compete with each other for watershed. In the lower courses of the river the original plain surface will have disappeared to some extent: the divides will begin to be smoothed off; the spurs rounded and the descent to base level will be steep but not precipitous.

This is still a youthful stage, but the more rounded outlines towards the lower levels shows that the erosion has proceeded beyond the phase of extreme contrast. Strictly speaking, the whole of the original surface has been somewhat lowered, but the effects will be much less evident where the rivers are too small in volume to widen their valleys rapidly. The whole area will therefore appear to vary in stage from the inland to the sea.

A further stage in the cycle, which may be called sub-mature, is reached when the smoothing-out process has gone well over the area, as in Fig. 73 (*b*). The rivers by this time have shifted their divides considerably and several captures of less active streams by the more active will have taken place. The harder bands of rock will have resisted erosion and will have taken a prominent part in its guidance. Thus, the subsequent streams behind the hard belt will have been active in smoothing out their basins, while the main stream, where it cuts through the belt, will still be running in an apparently youthful narrow valley. The land forms due to deposition in the lower courses will also begin to be prominent, the waste material being laid down as deltas, flood plains and river basins according to circumstances.

The truly mature stage presents land forms which are still further rounded, and there is a much broader belt of lowland where deposition is nearly equal in amount to erosion. The old plain (plateau) can be just discerned by the regularity in height of the highest hills, and is known as a dissected plain.

It will be noted, however, that the degree of maturity will appear to vary in different parts, the areas of soft rock being much more smoothed than those of hard rock, although the age of both is the same.

The latest stage, which is sometimes known as senile, is marked by the whole area being of comparatively low relief, the harder residuals merely appearing as rounded hills or "monadnocks" and the rate of erosion being almost equalled by that of deposition.

CHAPTER IX

MAJOR LAND FORMS

IT has been seen that the main factors in determining the relief of an area are the structure of the rocks at the surface and their varying resistance to erosion. But there are other factors which at times may be of almost equal importance, such as the nature of the climate and height above sea level.

Certain typical cases of the relation between erosion and structure may be examined.

Horizontally-bedded Rocks

When the stratification is more or less horizontal the land forms take on typical and simple characters.

The natural tendency will be for the harder and more resistant beds to dominate the relief, for they will outlast the softer beds. Thus, hills will tend to be capped with the harder layers and assume a somewhat tabular form. The slopes also will be affected as to profile, the harder beds furnishing the steeper gradients on normal slopes, and even giving a stepped or terraced appearance to the sides of the hills.

In general, the topography will vary according to whether the harder beds are below or above the softer. Where the softer beds are uppermost the relief will be smooth and rounded, because the degrading of the river beds will be delayed when it reaches the harder rock, and there will be time for surface erosion to "mature" the forms of the softer beds.

On the other hand, when the harder rock is uppermost, the river, on finally cutting through it, will degrade its

bed much more rapidly in the soft beds and by under-cutting the harder beds above will produce cliffs and steep slopes, and the general topography will be rugged and terraced. This, of course, is the state of affairs most favourable to the formation of waterfalls and sudden changes of level of the rivers. When there is a very great difference in the hardness of the two beds, as in the case of a hard sandstone overlying soft shales, the whole of the topography will be governed by this under-cutting of the softer beds by erosion; the valleys will tend to be steep-sided and plateaux will be formed on the divides.

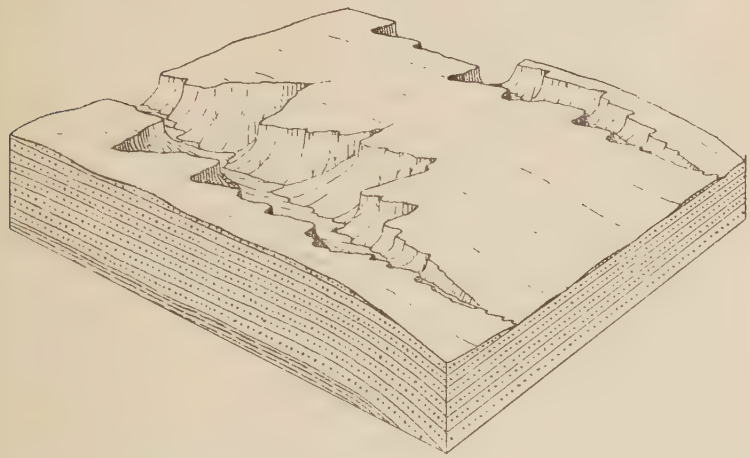


FIG. 74.—"BOTTLE-NECK" VALLEYS, COX AND GOOSE RIVERS, N.S.W.
(Somewhat Diagrammatic.)

A very good example of this structure on a large scale is described under the heading of land forms associated with folds; see p. 121, and Fig. 74.

The difference between the forms due to an arid and to a normal climate with level-bedded rocks will be one of degree rather than of kind. The waste, in the form of screes and talus slopes due to weathering, will accumulate more on the slopes in an arid climate since rain rarely falls to remove it elsewhere, but, except in extreme cases, where the accumulation of waste may suspend weathering, the same differential erosion will take place. The lack of a

vegetation cover in an arid region, on the other hand, allows the rain storms, when they do break, to act much more powerfully on the waste and assists in producing the clear-cut outlines of the familiar "buttes" and "mesas" of the semi-arid States of the United States of America.

When the hard layer is also pervious to water the undercutting process is further hastened, since the water will percolate through the hard rock instead of running over it and in the form of springs will concentrate its attack on the softer strata at the junction of the two.

The best example of this action is seen in the case of level bedded limestones, such as the Carboniferous Limestone of the West Riding of Yorkshire, which presents a bluff cliff-like aspect wherever erosion has cut through the limestone to the softer Coal Measure shales below. Hills of volcanic rock are also normally associated with flat-topped hills and cliffed slopes, excellent examples in Great Britain being the Campsie Hills, north of Glasgow.

Horizontal beds of varying degrees of resistance are responsible in many parts of the world for the characteristic topography, but it reaches its most spectacular form where the climate is arid enough to prevent very active erosion over the general surface, so that any rivers supplied by rain in other parts of the country exert a preponderating effect. They will then cut deep canyons, such as the Grand Canyon of the Colorado.

Beds with Uniform Dip

In this case also the theoretical effect on the relief can be easily foreseen, and will occur in nature over small areas.

At first sight one would expect the general direction of drainage to coincide with that of the dip of the beds, just as water will run down a tilted drawing-board in the steepest direction. But this will only happen in the ideal case when a sea floor of level beds is tilted uniformly above sea level. In all other cases the rivers will have to work through other materials before reaching the dipping beds.

Nevertheless, it is clear that the dip of beds of varying resistance will have a marked effect on the drainage system and hence on the topography.

It is easy to see that, starting with a peneplain of inclined rocks, the rivers will tend to deepen their valleys most along the weaker beds, that is to say, strike streams will have the advantage, so that one expects a series of parallel ridges of the more resistant strata standing up between the valleys carved by the softer. This is undoubtedly what would happen if the plain were truly flat to begin with. Normally the direction of drainage of an area is not due entirely to the geological structure at any particular period, but is inherited from the drainage of an earlier period. This "superimposed" drainage may therefore entirely disregard the present structure, though more commonly a kind of compromise is effected. It is often very difficult to say how much of a drainage system is inherited from earlier events and how much is due to present-day structure, and very different results occur in apparently similar areas. Thus the Thames runs generally in the direction of the dip of the beds it crosses, whereas the Ouse and the Trent are strike streams, as are several of the tributaries of the Thames itself.

The chief characteristics of a strike stream follow from its origin. Since it has eroded its valley in the softer strata it will tend to be asymmetric, with one side of its valley, the down-dip side, steeper than the other. When this is carried to a certain degree the result is an escarpment of a more or less marked character; the greater the contrast between the resistance of the beds concerned the more marked is the escarpment.

The Chilterns present an example of this, the Thame, flowing through the Vale of Aylesbury, being a strike stream. The Cotswolds are a little less obvious instance of the same thing, the Severn-Avon river system here causing the escarpment. Much more striking examples can be found in country of stronger relief.

The cross section of the valley of a strike stream will

tend to vary but little along its course, but in the case of a river flowing in the direction of dip, either with or against the dip, it will be quite the reverse. For in this case the river will be crossing beds of different resistance and will rapidly cut down the soft ones while it is held up by the hard ones. In the extreme case the result will be steep valley sides or gorges where it passes through the resistant beds and broad mature-looking valleys where it passes through the least resistant.

When the dip of the rocks is slight there will be interesting minor land forms which will vary according as the gradient of the stream is less or greater than the dip of the rocks. Where one bed is much harder than others there will be a tendency for the gradient of the stream to accommodate itself to the dip of that bed and flow along it for some distance and descend in a waterfall or cataract to the next hard bed. In general, when the gradient of a stream is down-dip its bed will be smoother and its valley section more uniform than when the gradient is against the dip, for in the latter case it will cross far more beds in a given distance.

Folds

The effect of differential erosion on the successive beds of a series is seen to greater perfection in the case of simple folds than in beds which have a uniform dip, since each land form will tend to occur twice, once on each side of the fold, as in Fig. 44 (pitching anticline). Many examples of this simple duplication of land forms are known, but, in general, there are other factors, which modify the case so much that the analysis is far from simple. For reasons stated fully in the last chapter one would expect the general direction of drainage in a folded area to be parallel to the axis of folding: that is to say, there should be a preponderance of strike streams. In fact, where this is not the case and the rivers consistently cut through harder beds at right angles, one must look for the antecedents of the area for explanation.

The different rate of erosion of anticlines and synclines is a prominent factor in the relief of such areas, and usually it is the anticline which suffers the most rapid degradation.

The reason usually given for this is that the beds on the crest of an anticline are in tension and therefore more open to attack, whereas those in the trough of a syncline are in compression and therefore more resistant. This is true, but is not a complete explanation.

Assume, for instance, a case such as in Fig. 75, where two streams of equal power run parallel with each other in an anticline and a syncline. The sides of the anticlinal stream, being against the dip, will expose a greater number of the beds than those of the synclinal stream which slope with the dip.

The synclinal river, when it meets with a broad hard band, will be held up by it in its cutting down and the valley will tend to concide with the curve of the fold.

The anticlinal river, on the other hand, will seize upon each softer bed in the series and form escarpments of the harder beds which it will rapidly undercut.

In a word, the drainage upon an anticline has a better chance to attack the weaker beds than upon a syncline. Consequently it is usually found that isolated mountains which are residual, i.e. the last portions of a folded area to resist degradation, are portions of synclines, the anticlinal folds having been worn away.

However, the former drainage plan of an area is inclined to persist for a long time, and there are many areas where the drainage does not accord with the present structure, since it originated on a previous one which has now quite disappeared. An instance of superimposed drainage is the radial direction of rivers in the Lake District of North-West England. This plan had its origin on a dome structure, with its centre near the present position of Helvellyn. The consequent rivers then cut their way down, radiating from the centre of the dome, and by the time the original surface rocks had been cut through and entirely removed the radial arrangement was much too

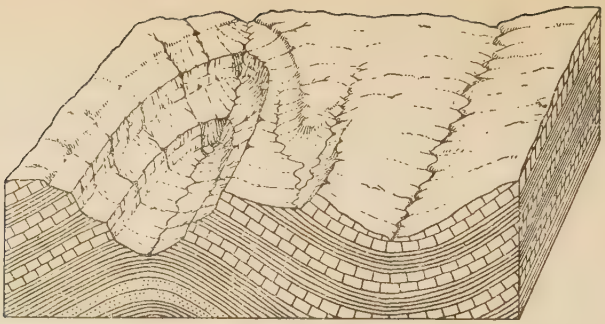


Fig. 75.—Erosion of Folds.

Showing that erosion is more effective along the crest of an anticline than along that of a syncline.

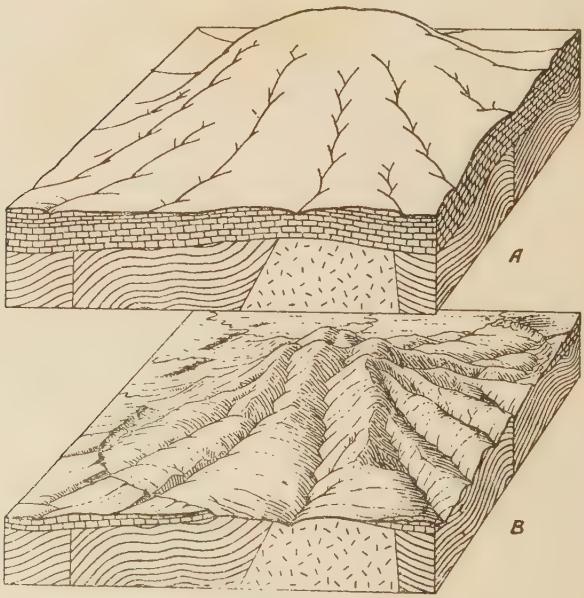


Fig. 76.—Superimposed Drainage.

A. Folded and faulted rocks overlain by a newer series. A dome uplift takes place and the consequent drainage system radiates from the centre.

B. Denudation removes the newer series; the radial drainage system is transferred to the exposed core of older rocks and hence continues its existence independently of the structure lines of this earlier series.

firmly established to be altered by the complex structure of the older rocks which now form the surface. The same kind of persistence of original direction is found in the

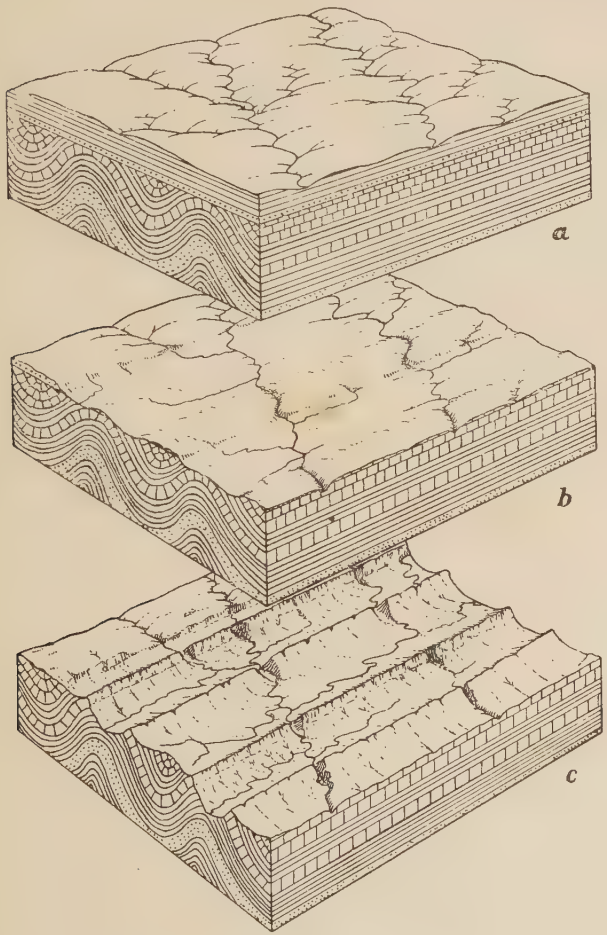


FIG. 77.—SUPERIMPOSED DRAINAGE.

To show how a Stream superimposed obliquely on folded strata will develop on cutting down into them.

case of a drainage system superimposed upon simple parallel folds, though the ultimate direction of the rivers will more and more nearly approach the direction of folding.

Fig. 77 is a diagrammatic representation of this. In

(*a*) the main river is flowing in a consequent direction over slightly inclined strata which rest upon a series of simply folded beds. When the river reaches the folded strata whose axes are oblique to the consequent direction, it will be able to erode more easily in the direction of the fold axis than any other. The first visible sign of this preferential erosion will be in the formation of subsequents which will tend to follow the strike direction and flow into the main stream obliquely. But the main rivers will continue in their original direction cutting through the escarpments as they are born by the action of the strike tributaries. Though a main river may be captured for part of its course, the old channels through escarpments will continue to exist for some time as "wind gaps" until, with the gradual lowering of the land surface, they disappear entirely.

CHAPTER X

MINOR LAND FORMS

THE early chapters of the Earth's history are written in the rocks and interpreted by the geologist both as palæontologist and stratigrapher, but the latest chapter affords little evidence from either the order of superposition of beds, or the contained fossils. Often enough, in fact, there are no deposits at all, but merely the negative evidence of erosion which has been going on over an area.

In the most recent history of an area, therefore, the comparatively minor land forms are of great importance. It is impossible to follow these in detail, but a few types which are of common occurrence may be mentioned.

Fluvial Land Forms

In general it is the land forms connected with rivers which are most fruitful in supplying evidence of what has been going on in the recent past, so that the geologist and geographer is much concerned with them.

Of these the forms due to the rejuvenation of rivers are perhaps the most striking and easy to recognize. When by some means the gradient is increased the fresh energy thus given to the river will find expression in rapid degradation of its bed, producing the effect of a valley in a valley, with the later slopes much steeper than the older. The gentle slopes of the mature valley rising above the steep sides of the younger valley is a marked feature of rejuvenation and there are many examples of this both on a large and on a small scale to be seen in many parts of the world.

Where the rejuvenation takes effect along the lower reaches of a mature river, in many cases the river will

FIG. 78.—RIVER TERRACES IN THE NEIGHBOURHOOD OF LONDON-ON-THAMES.

re-erode the deposits laid down by itself, and these will be rapidly cut into. Many characteristic land forms will result, the most striking being incised meanders and high level terraces.

The analysis of old river terraces is almost a study in itself and can be extraordinarily complex. For instance, a river, after reaching its grade towards the end of a cycle, will build up its bed by deposits laid down by itself, the older being at the base of the series. If, now, rejuvenation takes place, a new valley is cut out of these older gravels and after a time a fresh series of gravels is laid down. Should parts of the original terraces still be left, it becomes difficult to say what was the sequence of the gravels from their surface indications. The matter becomes still further complicated by the fact that a catastrophic flood may form a terrace high up the sides of the valley in amongst original deposits of the older series.

It must be noted that regional uplift is not the only cause of rejuvenation though it is the only one which acts upon a large scale. Active marine erosion may cut back the shore line rapidly and give rise to the type of rejuvenation shown in Fig. 79, though in this case regional uplift still no doubt in progress is also a contributory cause.

It is also possible for rejuvenation to be due to change of climate, especially in arid regions.

A common cause of local rejuvenation is the capture of the headwaters of one river by another. The beheaded river, having lost much of its supply, loses its energy and the rate of erosion slows down. At the point of capture, however, there is a sudden increase of gradient which enables the captured stream to begin eroding its valley at a greater rate. In such a case the eventual contrast in topography between the captured and beheaded parts of the original stream is usually very marked.

While a sudden acceleration of the rate of erosion can be recognized and analysed by fairly well-defined land forms, the converse of this, namely the slowing down of erosion by submergence or other cause is, however, not so

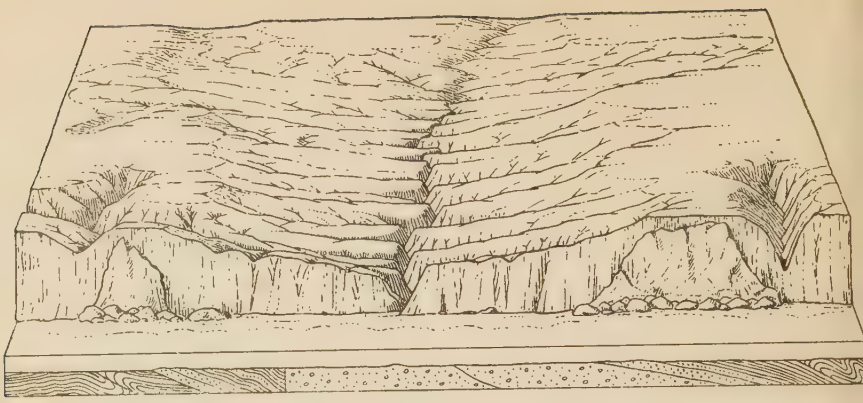


FIG. 79.—SOUTHERN SIDE OF THE SANTA ELENA PENINSULA, ECUADOR.
Rejuvenation due to rapid advance of sea and recession of sea cliffs. The ravines on the right and left were once tributaries of the main valley.

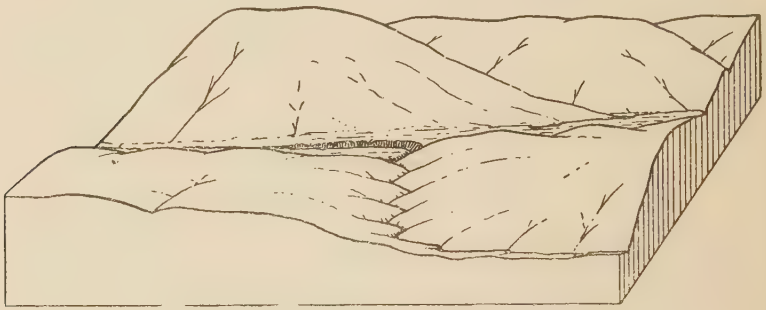


FIG. 80.—REJUVENATION BY BEHEADING.

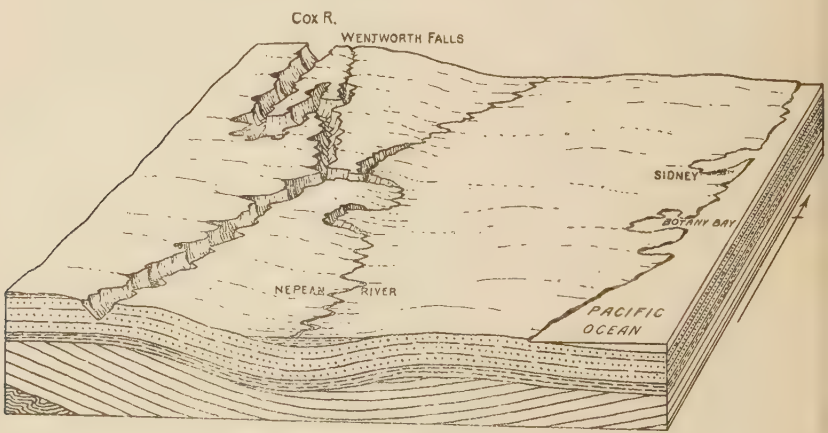


FIG. 81.—NEPEAN RIVER, N.S.W.
The monoclinal fold on the west arose so slowly that the river remained in its course cutting down deep gorges. Triassic sandstone and shale rest unconformably on Permo-Carboniferous Shales.

easily discerned. It will, of course, result in a greater rate of deposition by the river itself in its lower reaches, but that does not give rise to any very conspicuous feature and one has to go to the mouth of the river for something more striking. In the case of young valleys the drowning by submergence at once forms characteristic sea inlets, for example the "rias" of Cornwall, which incidentally form useful harbours. Moreover, some measure of the amount of depression can be gathered by the distance to which tidewater reaches and by the slopes near the mouth of the drowned valley. If the land, however, were low lying the effects would not be very marked, for although a wide estuary would be formed, a feature which is normally due to submergence, the form of the river bottom would soon be altered by deposits and the amount of submergence would not be easy to determine.

So far the phenomena of uplift and depression have been spoken of as if they were sudden events, whereas they are normally spread over very long periods during which the rivers accommodate themselves to the changing conditions all the time. Careful examination will often reveal signs of this change having been gradual: a remarkable case is shown in Fig. 81. Here the Nepean River running parallel to the present coast of New South Wales was subjected to the slow tilting movement which ultimately led to the formation of the monocline of the Blue Mountains. The process was so slow that the river was able to keep pace with it, cutting down its original bed instead of moving laterally. The result is remarkable, since the river, after flowing over a broad valley, suddenly enters a gorge at the base of the monocline and then emerges on to its original plain once more.

Vertical movements of the crust are not, however, universal and many minor details of recent history would be missing if movement of this kind had to be depended upon for evidence.

The formation of a flat valley by a river is a process which takes a very long time and its various stages follow

a plan which can be seen in operation to-day, although they may be difficult to unravel in the past. The extraordinary flatness of the valley floors of many mature rivers is a feature which is puzzling until the steps in its formation are thoroughly appreciated. What is seen is a sluggish stream meandering through thick sands and gravels which are almost perfectly level up to the sides of the valley. The valley of the River Lea to the north of London is a good example, for there the uniform level ends quite abruptly against what may be called the original valley side, which has a marked slope.

Two things must be realized before any adequate picture of the process can be arrived at. The first is that the greater part of the deposition goes on during heavy floods, when the water spreads right across its valley floor and drops its load far from the actual stream bed of normal times. The second is that the meanders themselves are constantly working down the valley, removing material from their concave bends and depositing it on their convex bends, and occasionally reaching the sides of the valley, there effecting some fresh cutting back of original material. It is this progression of the meanders down the valley which makes the deposits of a flood plain so complicated and which sounds a warning that order of superposition must not be relied upon too much to give a time factor in such a case. It is one of the reasons why the texture of the deposits in any gravel pit is usually so variable and of so little value in deducing the recent history.

The method of investigating river terraces can be given only in general terms, for there will be infinite variety in the conditions and circumstances. A point of first importance is to find the highest gravel terraces and to establish, if possible, their relative age. The height above datum level is clearly of importance since patches on the same level will be approximately of the same age. The character of the deposit itself is not without value, since it may indicate the source of the material, but usually very little can be inferred from the thickness and texture.

The shape, or rather the contour, of the original valley sides may be important, especially where the high level terraces are massive and therefore give a false appearance to the shape of the valley. The most promising places for examination are those where prominent tributaries enter the main valley, for here, if anywhere, there may be traces of a section cut through the older valley floors. Little can be added to this beyond the suggestion that more is to be obtained by examining in detail across the valley than by tracing deposits along its length.

Glacial Land Forms

In the regions of the world where the action of glacier ice is dominant, what may be called glacial land forms occur, the main outlines of which are probably familiar to the reader. The tendency for the valleys to be comparatively straight and shaped like a U in section, the occurrence of "hanging" tributary valleys and the deposits typical of ice action, are the subject of an extensive literature in itself. The predominance in cold temperate countries of the land forms, due to the Pleistocene Ice Age, now being transformed by fluvial action, adds complexity to the subject which is too great for adequate treatment here.

One or two warnings may be given, however, and some indications of the directions in which field study may be carried out.

In the first place it is necessary to realize that land forms due to ice alone are almost unknown, for even in the full rigour of an Ice Age—as is now the case on the Antarctic Continent—there is sufficient water action going on for short periods to modify the work of the ice considerably. By glacial land forms, therefore, is meant fluvio-glacial forms, and the emphasis tends to be on the former rather than the latter part of that hybrid phrase.

It is therefore not surprising that the interpretation of land forms due to this combined action of ice and water is exceedingly difficult and is a matter of keen debate or of directly opposing views.

There are certain things, however, that water alone cannot do, such as causing striations, laying down moraine débris, blocking tributary valleys and leaving erratic blocks at high levels: it is for the field worker to recognize and appraise these phenomena. Certain observations and measurements suggest themselves as obvious, such as the determination of the direction of flow of the ice by the evidence of striæ, the origin of the erratics, and so on. Similarly the height above the present valley at which obvious moraine material is still found will give some measure of the maximum thickness of the ice sheet, and the zone of greatest deposit of moraine may define the greatest extension of the glacier or ice sheet. Carefully surveyed and drawn sections across the valley may show the extent of the ice, and mapping of the occurrences of moraine material may define the successive stages of the advance and retreat of ice, but these are observations which are usually beyond the resources of the individual, who must be content with a more intensive study of a small area. Indeed, a really exhaustive study of one patch of moraine débris may be more profitable than an extended observation over a wide area, especially if the section available extends down to the original valley floor and is not high up on the sides of the valley, where only lateral moraine hills have gathered. If the glacial "till" or boulder clay is uniformly without structure or stratification, there is little to be learnt from it, but if there is banding or regularity of deposit it is important to inquire into the reason.

From the above it will be realized that for the student of glacial phenomena a pick and shovel are more appropriate implements than hammer and chisel. It may be added that a careful study of the land forms immediately below a retreating glacier in a Swiss valley is a more useful training than any amount of reading.

Marine Land Forms

The study of coastal erosion and deposition is another branch of geomorphology which is rapidly assuming the

proportions of a separate study, and the refinements with which it deals are quite beyond the scope of this book, which cannot go farther than directing the attention to main principles and to a few types.

Since the great majority of rocks with which the geologist deals have been laid down in proximity to coasts and are partly a result of their erosion, it is clear that the action going on at present should be of great interest.

This action is of course both destructive and constructive, the denudation taking place mainly, but not entirely, between tide marks and the deposition usually, but not always, in deeper water.

In special circumstances, however, one is concerned rather with land forms caused by marine erosion, and the most familiar of these is the sea-cliff, which can be extended to mean the slopes, more or less steep, caused by wave and tide action.

The factors which control the slope are similar in kind to those which control the topography of a river valley, varying with the kind of rock forming the shore and with its structure, and depending in a high degree upon the nature of the jointing or "habit" of the rock.

Consequently the best conditions for the formation of a perpendicular cliff are the occurrence of hard beds on softer beds, the more rapid erosion of the basal beds tending to produce an overhang. Vertical cliffs may also arise from other causes; in a porous homogeneous rock such as the Chalk, for instance, steep cliffs are formed because the softness of the rock enables wave action to have a maximum effect while the lack of surface water reduces the subaerial denudation. The action is assisted further by the frequent occurrence of springs at the base of the cliff. Again, in the case of very hard homogeneous rocks the action of the comparatively slow subaerial agents will be more than equalized by the more rapid action of the waves, which are assisted greatly by vertical jointing, a common occurrence in such rocks.

On the other hand, where soft rocks overlie hard ones

or where other circumstances enable the land processes of denudation to be more active than the marine processes, the slope will be gradual.

It remains for the student of land-forms to ascertain the exact cause of the sea-shore slopes; indeed, there is

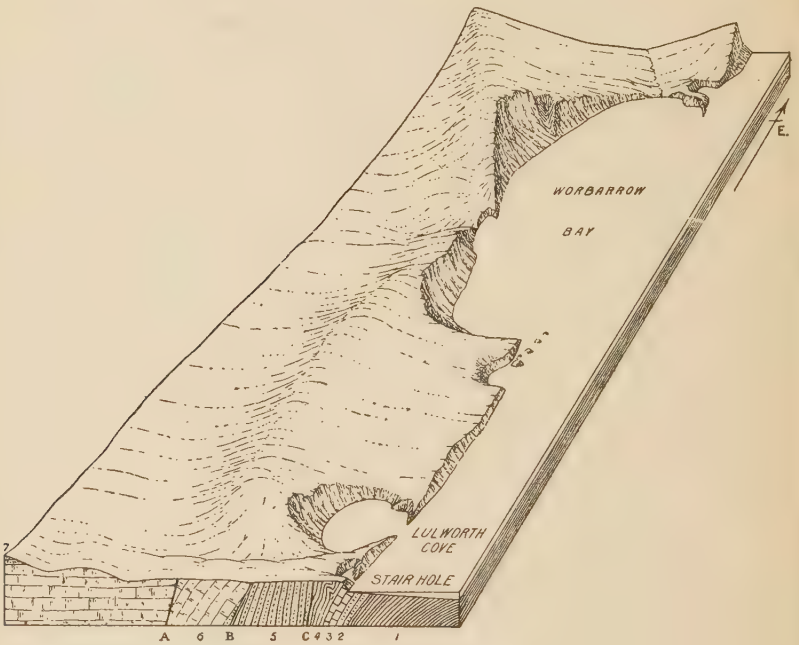


FIG. 82.—PART OF THE DORSET COAST.

Sheet 342 N.S. Area shown, 3½ sq. miles.

A, Isle of Purbeck Thrust Fault. B, Crush plane causing non-appearance at the surface of both the Upper Greensand and Gault. C, Crush plane squeezing out the Upper Purbeck.

1, Kimmeridge Clay. 2, Portland Sand. 3, Portland Stone. 4, Lower and Middle Purbeck. 5, Wealden. 6, Chalk. 7, Reading Beds.

The strata on the south side of the Isle of Purbeck fault being highly inclined, the hardened chalk gives rise to a long narrow ridge, the Purbeck Hills, of which the ridge in the foreground, Bindon Hill, forms the westward extension. This fault runs due east, veering somewhat to the north at Worbarrow Bay.

The Portland and Purbeck rocks give rise to a wall-like barrier to the advance of the sea. Three stages in the penetration of this barrier are illustrated. In Stair Hole a small gap allows erosion of the softer Purbeck and Wealden. In Lulworth Cove the gap is wider and the excavation in the Wealden is greater, but having reached the chalk on the north, the cove is acquiring an oval form, since erosion is easier on the east and west sides. In Worbarrow Bay the gap is a mile and a half wide and the chalk proves an effectual barrier northwards, so that a flattened oval outline of the coast marks the third stage.

no better exercise for him than to walk along a sea-shore and endeavour to account for the differences in the slope and character of the shore-line. This will be the more instructive if the coast happens to be formed of sedimentary rocks which have been subjected to a certain amount of

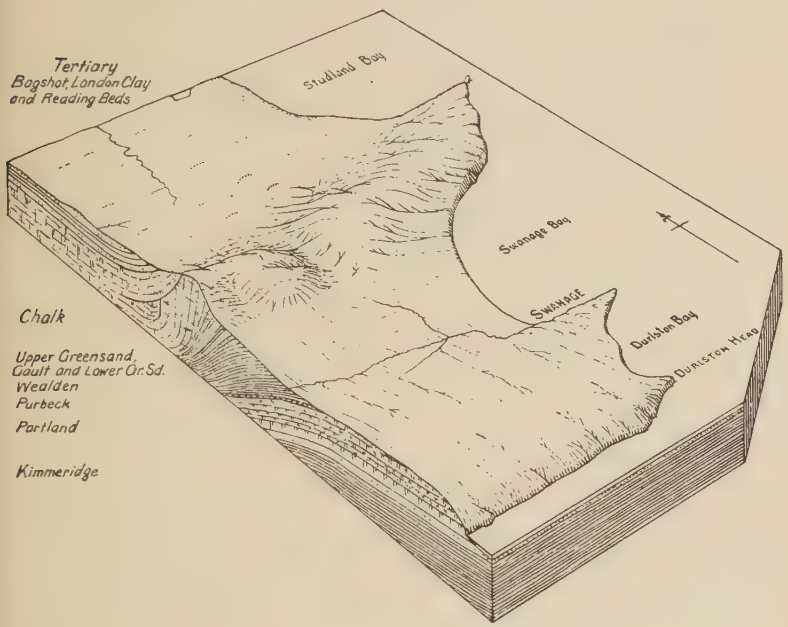


FIG. 83.—EAST COAST OF THE ISLE OF PURBECK.

Marine erosion, causing deep sweeping bays in the softer beds (Tertiaries, Wealden, Purbeck) and forelands when the harder beds (Chalk, Upper Purbeck, Portland) outcrop.

folding and faulting, such as the Dorset coast shown in Fig. 82.

The aspect of the coast, whether exposed or sheltered, has much to do with the land forms produced, as also has the depth of the water, since shallow water waves can do less damage than those upon a steeply shelving coast. For this reason headlands tend to be steep while the slopes in an embayment tend to be gentle. To summarize, the nature of the slope is largely a matter of the balance between subaerial and marine erosion. The continued activity of

wave action depends also, it should be noted, on the removal of the detritus to deeper water, otherwise the water becomes shallow in course of time and the erosion process becomes retarded.

The deposition of material above the sea level is, as stated above, the effect of special conditions which are sometimes very complex indeed. The set of the tidal currents is partly responsible for the longshore drift of material, but often the direction of the dominant winds and waves is an even more powerful agent.

The formation of spits and banks of sand and shingle, such as the nesses of East Anglia or the Chesil Bank of Dorset, is due to the interaction of these forces, and the study of their origin is a somewhat difficult one. In the main, however, one must recognize that some at least of the products of marine erosion do not find their way to rest in deep water but are piled up to form protective strips to other parts of the coast, and even to increase the area of land.

Thus far, coasts of comparative stability as to level have been noted, but a fresh set of characteristic land forms comes into being when the coast is undergoing slow submergence or elevation.

In the case of submergence estuaries and drowned valleys tend to be formed, and there is a maximum attack of the sea upon fresh levels of the land. The amount of "cliffing" formed is, in an approximate way, a measure of the pause in submergence, for continual submergence will drown the immature cliffs. Offshore islands and an indented coast are obvious forms of evidence for such submergence.

In the case of emergence, on the other hand, there is a tendency to the formation of an even coast line of low aspect as the former sea bottom rises above sea level. The minor land forms to be expected in such a case are raised beaches on a detrital coast and raised rock platforms or benches on a rocky coast. Both of these are recognizable in many places round the coast of Scotland, and represent

both a definite degree of elevation and a marked pause in the movement at that level. The former sea cliffs, now removed from the attack of the waves, will gradually become gentle slopes under the action of subaerial weathering.

In general, it should be clear that the minor land forms of valley and shore lines are due to the interaction of structure and erosive forces, which follow well-defined laws however obscure individual cases may appear to be.

CHAPTER XI

THE CONSTRUCTION OF BLOCK DIAGRAMS

THE advantages of block diagrams as a means of illustrating geological principles, the connection between surface and underground structure, and actual portions of the Earth's crust, have been pointed out in an earlier chapter, and, it is hoped, have been emphasized by the various diagrams throughout the book. A further use is as illustrations for lectures, reports and scientific papers, both geological and geographical.

In order to draw diagrams correctly, the principles of perspective drawing must be understood. In this chapter the matter will be discussed in considerable detail for the benefit of those who wish to make finished drawings from geological and topographical maps.

Block diagrams can be drawn in either isometric projection or in perspective.

In the former method all lines receding from the observer are drawn parallel and true to scale: in fact, the resulting figure can be considered as a limiting case of perspective drawing where the vanishing point is at infinity so that convergence of receding lines and foreshortening are nil. The chief advantages of this are simplicity of drawing and the direct transfer of measurements on a true scale to receding surfaces. But the artistic effect is poor and the drawing appears quite unnatural in most cases: so, for the purposes of graphic illustration, a perspective drawing is preferable. All drawings in this book are done by this method which alone will be described.

First it will be necessary to give a description of the

principles of perspective, though the idea may be familiar. When a plane horizontal surface is viewed from a point above it, a ray starting from a point on the surface at a very great distance will travel to the observer's eye along a line almost parallel to the surface: a ray from infinity on the surface can be considered as actually parallel. Vertically below this ray appears surface, above the ray appears absence of surface. Considering a fan of such rays, the division between surface and non-surface is a straight horizontal line and is called the horizon.

In practice, the power of the eye to resolve distant groups of points is limited, as is also the extension of plane surfaces: a calm sea is the nearest approach to a plane of any magnitude in relation to the power of the eye, and even this is only approximately plane. However, the general effect is obtained and the horizon corresponds to an infinite distance with sea below the fan of rays and sky above.

First, then, there is a horizon at a great distance. All lines parallel to the plane and receding from points near the view point appear to end in the horizon. Such starting points of lines may be above the view point, in which case the lines appear to slope downwards to the horizon: or, on a level with the view point, when they appear horizontal and coincide with the horizon: or, below the view point, when they appear to slope upwards to the horizon. Furthermore, two or more such lines parallel to one another and to the surface will converge to the same point on the horizon. This point is called the vanishing point of the group. Another group of similarly parallel lines passing in another direction converge to a common point elsewhere on the horizon, the vanishing point of that particular group.

To be rather more practical, consider the flat block KMLB, drawn in full lines in Fig. 84, lying in a plane and observed from a point E above the plane. It is immaterial whether one imagines the ray from the view point to the fore corner as horizontal and the plane tilted

towards the view point, or the plane horizontal and the ray inclined towards the corner.

The edges KM, BL, B′L′ are parallel to one another and to the plane on which the block lies: therefore they appear to converge at a great distance at a point Y, their vanishing point. Similarly the edges LM, BK, B′K′, another such parallel group, appear to converge at X, their

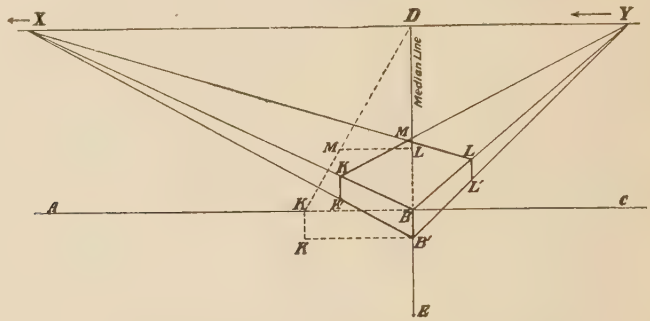


Fig. 84.—Relation of One- and Two-Point Perspective.

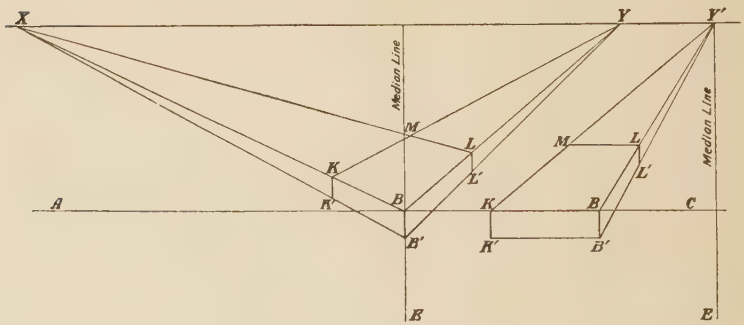


Fig. 85.—Block Construction.

vanishing point. A line passing through X and Y is the horizon. The edges perpendicular to the plane, KK′, BB′, LL′, another group of lines, also have a vanishing point vertically below the plane, but since for a tilt such as is usually given to the plane, this point is at a comparatively great distance in a drawing and the lines (which represent the thickness of the block) are short, they may be drawn parallel and perpendicular to the horizon. This block is said to be drawn in two-point perspective.

Imagine the block to be rotated on an axis BB′, perpendicular to the plane on which it rests, say to the left. The two vanishing points move correspondingly along the horizon to the left, X at a more rapid rate than Y. When Y reaches the point D, on the median line EBD perpendicular to XY and drawn from the view point E through the fore corner B, X has receded to infinity to the left and KB, K′B′ become parallel. The position of the block is then as shown by the broken lines and what is known as a one-point perspective drawing results.

The median line is defined as the line drawn perpendicular to the horizon from the view point; hence in two-point perspective it passes through the fore corner of the block, in one-point perspective through the vanishing point of the group of receding parallel lines (see Fig. 85).

It is a simple matter to construct a block for the purpose of a merely general representation of surface features and geological structures.

First draw a horizontal line XY, the horizon (Fig. 85). At any distance below it draw a parallel line ABC.

(i) For a two-point perspective drawing choose a point B, as the fore upper corner of the block, on ABC, and two points, X, Y on the horizon. Draw BB′ perpendicular to the horizon. Making BB′ the required thickness of the block. Join BX, BY, B′X, B′Y. Take any points K, L in BX, BY: join KY, XL, lines intersecting at M. From K, L drop perpendiculars to meet B′X, B′Y in K′, L′. Then the perspective block KMLBL′B′K′ is completed. The median line passes through the fore corner B.

(ii) For a one-point perspective drawing choose a point B on ABC as one of the two fore corners of the block, and a point Y′ on the horizon as vanishing point. Draw a rectangle BKK′B′ representing the face of the block: this will be in its true proportions. Join Y′ to K, B, B′. From L, any point in BY′, draw LM parallel to BK, and LL′ parallel to BB′. Then the perspective block is completed. The median line passes through Y′.

It will be seen that by altering the relative distances

of X and Y on the horizon from the median line in case (i), or the median line itself and hence Y′ relative to the corner B in case (ii), different views of the sides are obtained. By making ABC closer to or further from the horizon for any definite positions of X and Y, or Y′, a finer or broader view of the upper surface of the block is obtained.

When, however, an actual example of a topographical and geological map is to be reduced to a block diagram, the diminution in size of features with distance has to be taken into account. Meridians and parallels of latitude, or some system of squares or rectangles on the map to facilitate correct drawing of features, have to be transferred to the perspective block. These lines close together according to a regular scale depending on the tilt of the block and the distance of the view point from the fore corner or edge. This matter is considered in the following series of diagrams.

Fig. 86 is a pictorial one designed to show the relation of a perspective drawing to the actual object.

The foreground represents a flat horizontal surface, such as a table, on which the view point or eye, E, is situated. EN is a line on this surface meeting the lower edge of a vertical sheet of paper ABCD (shown as transparent) placed at right angles to EN. This sheet represents the paper on which the perspective drawing is made.

Behind the sheet rises a narrow rectangular strip of material with the fore edge of its upper surface coinciding with the surface of the table and the lower edge of the sheet at FNG. The strip is inclined at some angle such as 35° to the table and, of course, is at right angles to the sheet. It is to be considered as of infinite length, though it is shown as broken off at the rough edge. In the picture it has been given a definite thickness for the sake of clearness, but this thickness is immaterial to the problem since actually one is concerned only with the upper surface of the strip. The strip is divided into equal sections at H, K, L, M . . . and is drawn without regard to perspective:

in fact, it is drawn in isometric projection. The median line is NOPQR . . .

Now what is required, to obtain a perspective view of this strip from the view point E, is to project the various points on it onto the sheet of paper ABCD.

Consider a ray from E to an infinitely remote point on

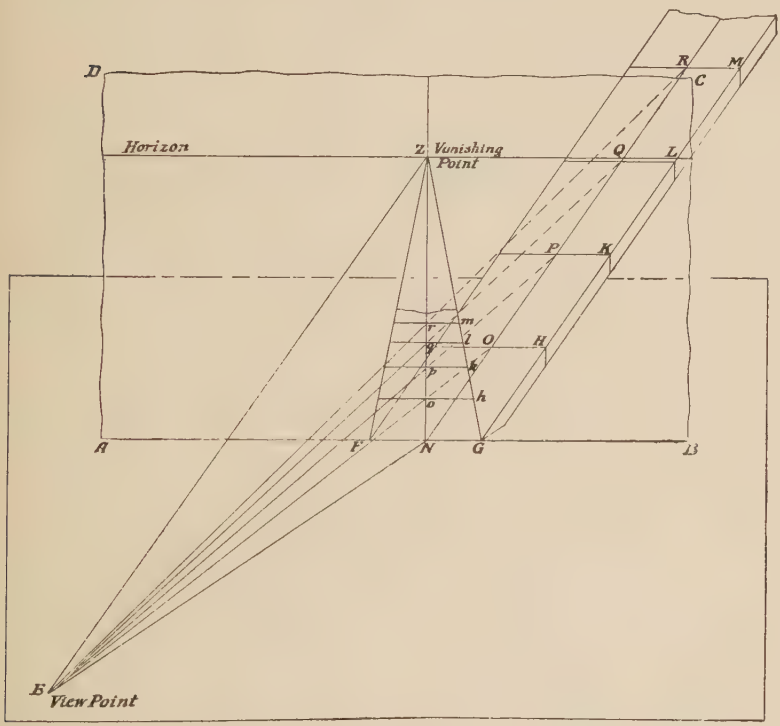


FIG. 86.—A PICTORIAL DIAGRAM TO SHOW THE RELATION OF A PERSPECTIVE DRAWING TO THE ACTUAL OBJECT.

the median line of the strip. Such a ray will be parallel to the median line. If this ray EZ be so drawn parallel to NR, it will cut through the sheet of paper at Z, a point vertically above N in the vertical plane containing EN, NOPQR . . . and Z. Point Z is then the vanishing point of the representation of the strip, and a line drawn horizontally through Z on the sheet is the horizon. By joining ZF, ZG, a true perspective drawing, ZFNG, of the strip

is obtained: ZG representing the side GHKLM, ZF the other side, and ZN the median line.

It remains to represent the cross sectional lines. Rays are drawn from E to the points O, P, Q, R . . . intersecting the sheet of paper at *o*, *p*, *q*, *r* . . . Horizontal lines through these points, *oh*, *pk*, *ql*, *rm* . . are the perspective representations of the cross sectional lines. It will be seen that they become closer together as the vanishing point is approached.

A formula for finding the height of the vanishing point above the fore upper edge of a block for any degree of tilt and for any distance of the view point from the sheet of paper can be found from this diagram.

Thus $\frac{ZN}{NE}$ = tangent of the angle $N\hat{E}Z$

= tan (angle of tilt)

Or, the height of the horizon line above the fore edge of the block equals the distance of the view point from the fore edge multiplied by the tangent of the angle of tilt.

The application of this formula will be shown later.

Problem I.—To construct in two-point perspective a square block tilted at any required angle (see Fig. 87).

(1) Draw a horizontal line XDY, the horizon.

(2) At any point D in it draw DBE at right angles to, and below XDY.

(3) Take any point B in DBE as the fore corner of the block.

(4) With B as one corner draw a square BFGH of any convenient size and disposed at any angle to DBE. This will be referred to as the "parent rectangle."

(5) Find a point E in DBE such that

$$\frac{DB}{BE} = \text{tangent of the angle of tilt.}$$

In the diagram DB = 1·61 units, the angle of tilt is 35°.

$$\text{Therefore BE} = \frac{1{\cdot}61}{\tan\ 35^\circ} \text{ units} = 2.30 \text{ units.}$$

(6) From E draw EX, EY parallel respectively to BF, BH, meeting XDY in X, Y. Then X, Y are the vanishing points.

(7) Join BX, BY. The fore top edges of the block lie along these lines.

(8) Join EF, EH: these lines intersect BX, BY at K, L.

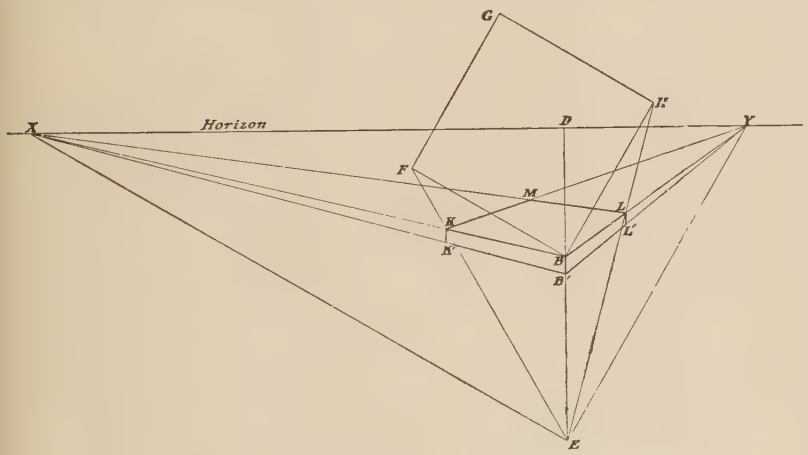


FIG. 87.—BLOCK CONSTRUCTION, TWO-POINT PERSPECTIVE.

(9) Join XL, YK: these lines intersect at M. Then BKML is the upper surface of the square block in perspective.

(10) Take any point B′ below B on the line BE, so that BB′ is the thickness of the block, which may be any convenient measure.

(11) Join B′X, B′Y and drop perpendiculars from K, L to meet these lines at K′, L′.

The block is thus completed and is tilted at the required angle.

Note.—Convenient measurements for a drawing which can be made on a sheet of paper 28 by 12 in. are:—Angle of tilt, 35°; DB, 4·9 in.; BE, 7·0 in.; sides of parent rectangle, 6·0 in.; angle DBH, about 30°.

This is a general construction. So long as the fore corner B is retained in any drawing whatever its scale or whatever the angle of tilt of the block, the rectangle BFGH can be placed in any position so as to give different views from E of its sides. Lines from E drawn parallel to the sides intersect the horizon at other pairs of points, the new vanishing points, which thus change their position on the horizon. But all blocks so drawn will still be tilted at the required angle.

Problem II.—To construct in one-point perspective a square block tilted at any required angle.

In Fig. 87 consider the limiting case where the square BFGH is swung round the point B as a pivot to the left (say) so that one side BH coincides with the direction BD and the other BF consequently becomes parallel with XDY. Then the lines from E parallel to these sides intersect XDY at D, one vanishing point, and at infinity to the left, the other vanishing point. In other words, it becomes a one-point perspective drawing, which is merely a special case of the two-point perspective, as was pointed out above.

The construction is shown in Fig. 88.

(1) Draw a horizontal line XD, the horizon.

(2) Draw a parallel line AB at a suitable distance below XD.

(3) Draw a line at right angles to the above, intersecting them at D, B respectively. D is the vanishing point.

(4) Find on this line a point E, the view point, such that

$$\frac{DB}{BE} = \text{tangent of the angle of tilt.}$$

(5) Construct the "parent rectangle," a square AFGH, on AB. Then AH is the fore edge of the block.

(6) Join DA, DH. Then DAH is the surface of a perspective block whose front edge is equal to the side of the required square and whose length is infinite.

(7) Join EG. This line intersects DH at L. Then L is the further right corner of the required block.

(8) Draw LM parallel to AH, meeting DA at M. Then AMLH is the upper surface of the block representing the square.

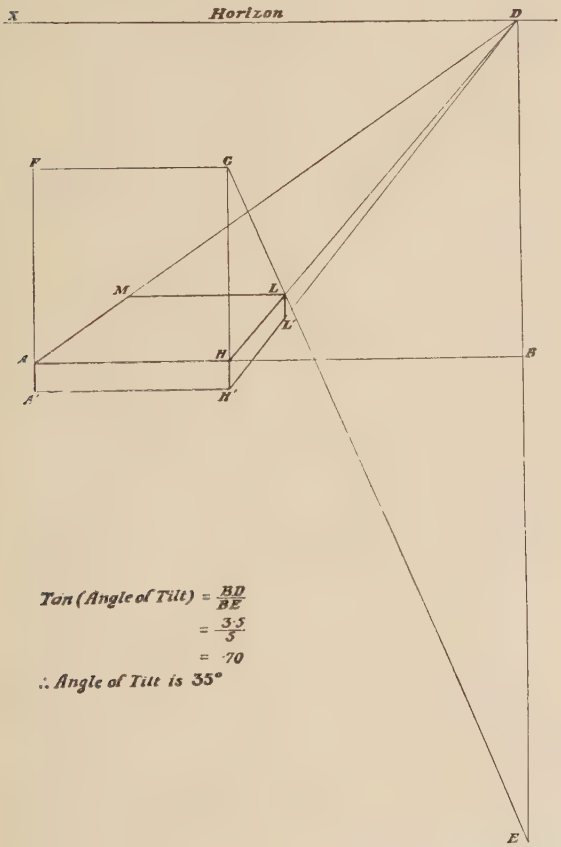


Fig. 88.—Block Construction, One-Point Perspective.

(9) Complete the block by drawing A′H′ parallel to AH and at a suitable distance from it, and by dropping perpendiculars from A, H to meet A′H′ in A′, H′. Join DH′ and drop a perpendicular from L to meet DH′ in L′.

Note.—Convenient measurements for a small drawing

are:—Angle of tilt, 35°; BE, 10 in.; DB, 7 in.; AH, 4 in.; HB, 6 in.

The parent rectangle can be erected anywhere on the line AB extended in either direction, so as to give rise to a block with a greater or less fullness of view of one side or the other, or, if about the median line DB, to give a block with no side visible. The parent rectangle should not, however, be taken too far away from the median position since distortion will arise: for the convention is, that the front face of a block in one-point perspective is normal to the view point and this convention becomes strained when the block is far to one side. The outer perspective edge should make an angle of not less than about 30° with the horizon for a tilt of about 30° to 40°.

It should be noted that for any definite position of the view point, horizon and distance of the fore edge of the block from them (i.e., for any given angle of tilt) the width of the block from fore to rear edge measured on the paper is constant, whatever is the position of the block, to the right or left of, or on, the median line. Thus in Fig. 88 the distance apart of the lines AH and ML is the same if the block is shifted laterally to any extent. However, as it is moved from the median line DBE to the left, say, AM lengthens, becomes in one position equal to AH, and eventually exceeds it in length, so that the resulting block, which is known to be a square, loses all resemblance to one. This is the reason why blocks should be chosen not too far from the median line, as noted above (see also Fig. 90).

Another way of looking at the matter is to consider a block in one-point perspective whose median line coincides with one of the receding edges. If the side containing that edge is now to be seen at all, the eye must be moved slightly to one side, or, what is the same thing, the block must be twisted slightly on its base. Now this is equivalent to the introduction of two-point perspective. So long, however, as the twist is not too great, the vanishing point of the horizontal lines of the front face may be considered as still remaining at infinity. These lines may therefore

be drawn horizontal, and the drawing does not offend the eye by appearing unnatural.

Problem III.—To construct a block tilted at any required angle, whose surface is divided into a system of rectangles.

That is to say, a block to represent on its surface some system of rectangular divisions such as parallels of latitude and meridians. This kind of block can also be considered as a composite one built up of a number of smaller ones fitted together.

A. Two-point perspective.

The procedure is the same as in Problem I, except that the parent rectangle, instead of being a single square, is a rectangle whose sides are marked off in lengths corresponding to the divisions required. In Fig. 89 the block is drawn, by the construction given above, to represent the parent rectangle. The subdivisions of the sides *a*, *b*, *c*, *d*, *e* are marked on the rectangle. E is joined to each of these points by lines intersecting BF′ in *a′*, *b′*, *c′* and BH′ in *d′*, *e′*. By joining Y to *a′*, *b′*, *c′*, and X to *d′*, *e′*, the required subdivisions appear on the surface of the block.

B. One-point perspective.

The procedure is the same as in Problem II, except that the parent rectangle AFGH in Fig. 87 is divided up into rectangles as required and lines are drawn from E, the view point, to the divisions on the side, to give intersections with the line from the corner of the block to the vanishing point. It is necessary in this case to join only the side points with E because the divisions along the fore edge are always true to scale. Fig. 90 shows a single and two composite blocks in different positions.

There remains the problem of representing parallel lines or lines inclined at a given angle on the sides of the block: that is, stratification.

A. One-point perspective.

(i) Take first the simple case of bedding planes dipping at a given angle towards the rear of the block, the fore edge consequently being the direction of strike.

In Fig. 91 from B set off BF equal to BB′: draw FG

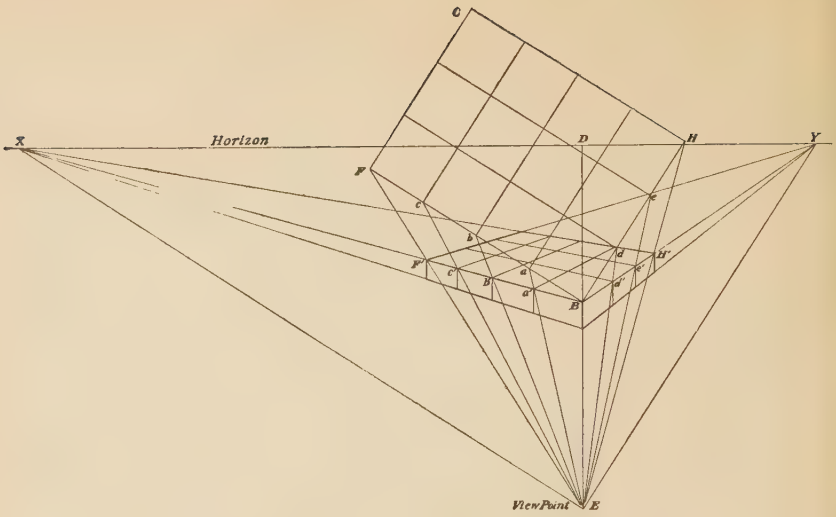


Fig. 89.—Meridians in Two-point Perspective.

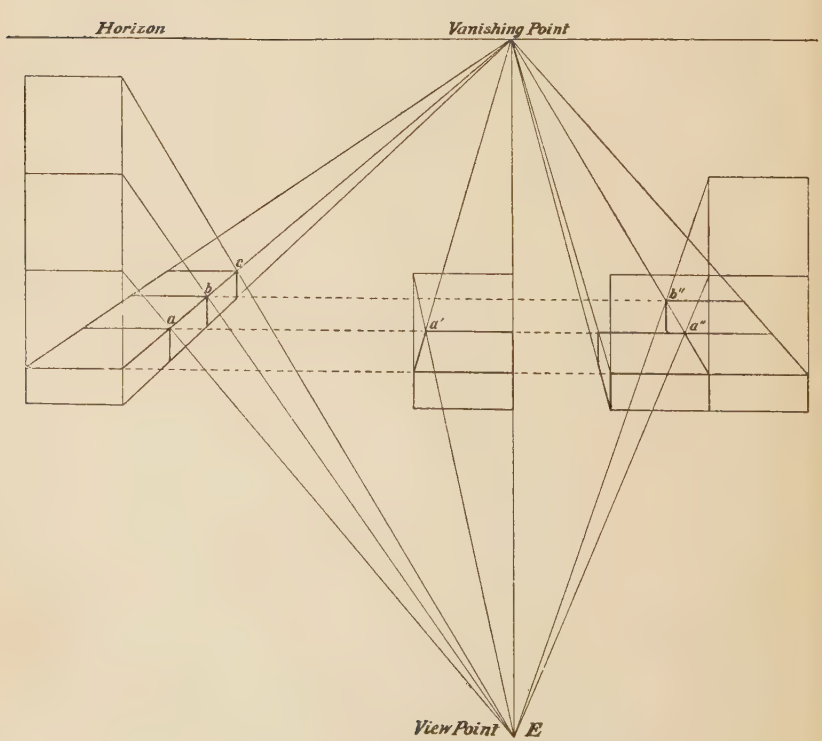


Fig. 90.—Meridians in One-point Perspective.

parallel to BC. The rectangle FGCB is a true plan of the perspective drawing of the side BHH′B′. Draw FQ making the required angle of dip (here 20°) with FG. FQ meets BC at Q. Join EQ: this line intersects BH in p, from which point drop a perpendicular to meet B′H′ in q. BpqB′ is then a perspective drawing of the rectangle FPQB,

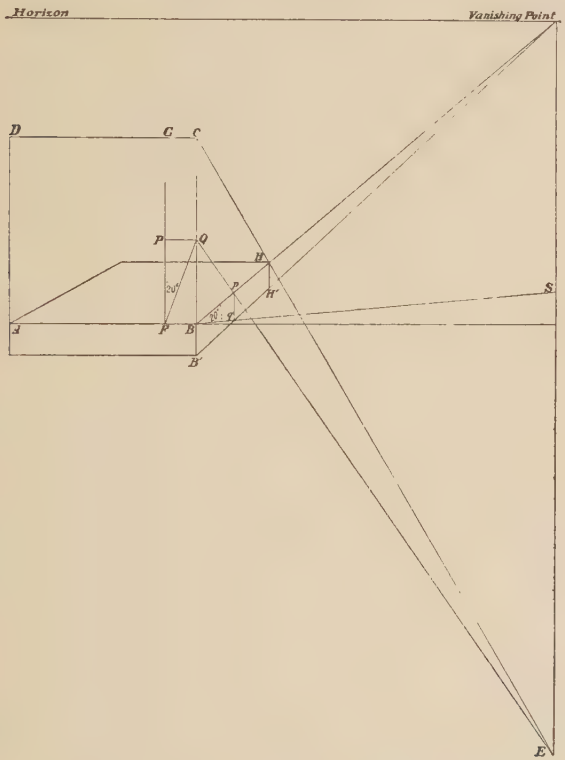


Fig. 91.—Inclined Lines on Block Faces.

in the same way as BHH′B′ is one of the rectangle FGCB. So Bq represents FQ and thus a line inclined at 20° to BH. Produce Bq to meet the median line from view point to vanishing point at S. Then S is the vanishing point of all lines inclined at 20° to the upper edge of the block drawn on the side BHH′B′. Radial lines from S to any points on BH and BB′ give a perspective representation of bedding planes on that face.

(ii) For planes dipping towards the observer a similar construction holds, but in this case the other diagonal B′p of the rectangle BpqB′ is inclined at the required angle: for B′p is a representation of the diagonal PB of the rectangle FPQB. Produce B′p to meet the median line produced above the horizon at a point S′. Radial lines from S′ are drawn as before to points on B′H′ and BB′.

In these two cases (i) and (ii) on the side of the block facing the observer, since there is no perspective, parallel bedding lines remain parallel to the fore edge.

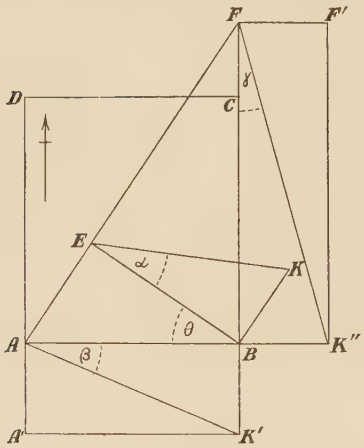


Fig. 92 (*a*).

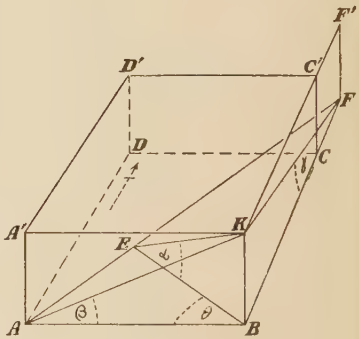


Fig. 92 (*b*).

Inclined Lines on Block Faces.

(iii) The general case of planes dipping in any direction not parallel to a side must be considered.

In Fig. 92 (*a*) ABCD is the parent rectangle, AD being, say, the north direction: BE the direction, $\theta°$ north of west, and $\alpha°$ the amount, of dip.

Draw AEF perpendicular to BE, meeting BC produced at F. On EB construct a right-angled triangle EBK such that the angle BEK is $\alpha°$. On AB construct a rectangle AA′K′B where BK′ = BK, and on BF a rectangle BK″F′F where BK″ = BK. Then the diagonal K′A will be inclined to AB at an angle β and the diagonal K″F at an

angle γ, the apparent dips as seen on sections along AB, BF respectively.

Fig. 92 (*b*) is a pictorial representation of the plan, Fig. 92 (*a*). If the rectangles AA′K′B, BK″F′F and the triangle EBK be imagined as rotated about their bases AB, BF, EB as axes, so as to stand vertically out of the plane of the paper, the three points K,K′,K″ become the one point K in Fig. 92 (*b*) and the plane AEFKA, inclined at a to the horizontal and dipping in the required direction or bearing, intersects the sides of the block along AK, KF which are the apparent dips on the two faces of the block.

Returning again to Fig. 92 (*a*), the construction there given is carried out on the parent rectangle and the angles β, γ obtained. These two angles are then utilized for the two faces of the block as in Fig. 91.

B. Two-point perspective.

A similar construction holds good for the three cases.

(i) Bedding planes dipping to one of the rear sides of the block.

Strike lines on one face converge to one vanishing point; dip lines on the other face converge to a point S *below* the horizon on a vertical line drawn through the other vanishing point: not on the median line as in the case of one-point perspective.

(ii) Bedding planes dipping to one of the front sides of the block.

As above, strike lines on one face converge to one vanishing point, but dip lines on the other face to a point S *above* the horizon, on a vertical line drawn through the other vanishing point.

(iii) The general case of any direction of dip.

The construction shown in Fig. 92 (*a*) gives the two apparent dips and these are utilized on their respective sides after the manner shown in Fig. 91. It must always be remembered that in two-point perspective drawing the vanishing points for bedding lines are on vertical lines drawn through the primary vanishing points on the horizon.

Fig. 93 illustrates several points discussed above.

The first block shows a series of strata dipping to the rear of the block: all stratification lines on the side converge to the point S on the median line. The second block EF shows a symmetrical anticline : the axis *ab* is vertical and the position of *a* on the line EF is found by the normal

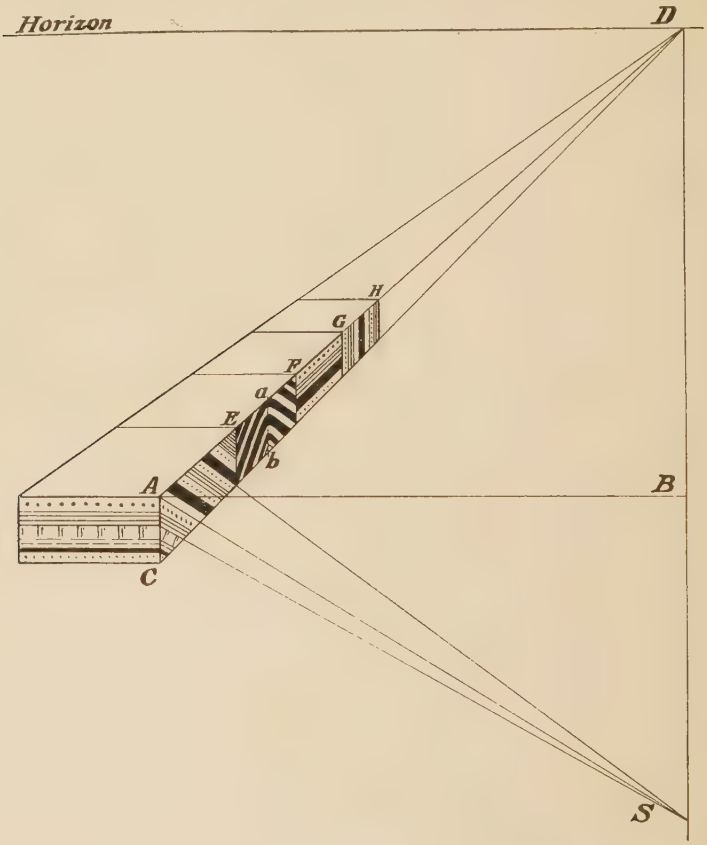


FIG. 93.—REPRESENTATION OF STRATA ON BLOCK FACES.

construction (Fig. 88). In plan (or on the parent rectangle) it is exactly half-way between E and F, but in perspective it is closer to F. The third block FG shows horizontal strata whose lines converge to the vanishing point. The fourth block GH shows vertical strata; the vanishing point of their lines is at a great distance below the horizon, hence they are practically parallel and are drawn so.

CHAPTER XII

BLOCK DIAGRAMS OF GEOLOGICAL MAPS AND STRUCTURES

THE boundaries of the particular area on the map which it is desired to convert to a diagram should be arranged so as to include the physical features on the surface to which attention is to be drawn and to give satisfactory geological sections along two sides explanatory of the structure. It is of course easier to make the boundaries rectangular, but the rules for drawing blocks apply equally for boundaries other than rectangular. In a case where space is important, as in a book, it is possible to remove corners of the block without impairing materially the value of the illustration, but the complete rectangular block should be constructed and the corners removed after the drawing has been completed, this being far simpler than attempting to reproduce a polygonally bounded area.

In general, where geological structure is simple, it is preferable to take boundaries parallel to the strike and dip or to axes of folding. With a complex structure boundaries should be chosen so as to give the greatest amount of information graphically on the two visible sides of the block as well as to include the topographical features depending on the structure. In cases it may be preferable to set one boundary due north.

The chosen rectangle is then marked off into a network of minor rectangles, which may be meridians and parallels of latitude or any arbitrary system of lines either parallel or oblique to the boundaries. For simplicity, a system of squares may be drawn fitting exactly between one pair

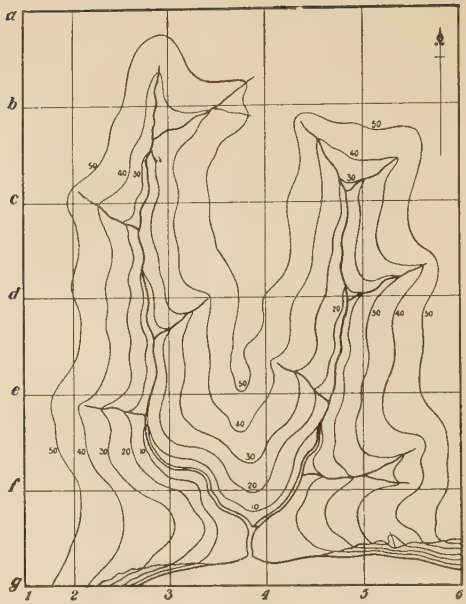


FIG. 94.—CONTOURED MAP.

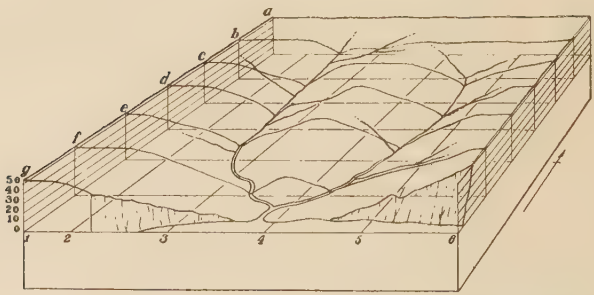


FIG. 95.—STAGE IN CONSTRUCTION OF BLOCK DIAGRAM.

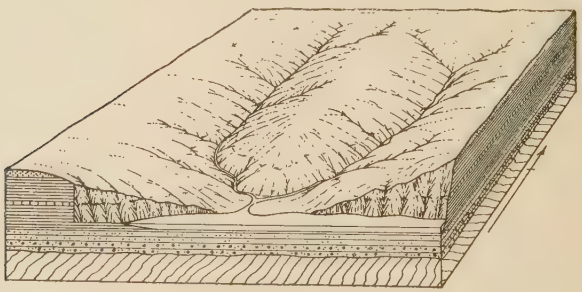


FIG. 96.—COMPLETED BLOCK DIAGRAM.

of opposite boundaries. Thus in Fig. 94 the north–south line *ag* has been divided into six equal parts, the east–west line into four of these parts and a fraction, and the network has been completed by drawing lines parallel to the sides through these divisions. Equally well, however, each side might have been divided into any number of equal parts to fit exactly into a side: a network of rectangles instead of squares would have resulted.

To avoid drawing many lines on the original geological map, it is preferable to mark in the boundaries only in pencil so that the marks can be removed afterwards without damage. A tracing is then made of the boundaries and the network is drawn on it. All contour lines are then traced off, preferably as fine dotted lines, as well as rivers, streams, lakes and other prominent features. The advantage of this is, that the rather heavy colours on the geological map obscure the contour lines: on a tracing the topography becomes quite clear for the purpose of reference when drawing profiles and sketching in form lines.

Now the block is drawn in any desired position according as the best view of surface and sides, to bring out the important points of topography and structure, can be obtained. A convenient tilt for most drawings is 35° to 40°. The scale depends on the purpose for which the drawing is required, or on the scale of the parent rectangle, that is to say, of the tracing; though if necessary the tracing can be enlarged or reduced by pantograph or freehand. Most of the drawings in this book of actual localities were made from rectangles taken on the One-Inch Geological Maps of Great Britain and reduced to about two-thirds by photography to fit the page.

The parent rectangle and its network is, then, put in lightly in pencil on the drawing paper in its required position after the horizon, fore corner of the block and view point have been determined and drawn. The block is then constructed as shown in Figs. 89 and 90.

The procedure will be easier to follow from the example, Figs. 94, 95 and 96, which show the topographical map,

a stage in the drawing and the finished block diagram. Topography only has been represented on the map since other lines showing boundaries of outcrops might lead to confusion. In the completed diagram the geological structure has been drawn in.

On the prepared block a scale of heights is drawn at each front corner. This scale usually has to be greater than that for horizontal distances, as is generally the case in section drawing, but it should not be exaggerated unduly, otherwise the valley slopes and other features will appear unreal. Lines are then drawn from the points on the scale at each corner to the vanishing point. Vertical lines *a*, *b*, *c*, *d* . . . are set up from the terminal points of the parallels *a*, *b*, *c*, *d* . . . of the map as reproduced on the block during its construction. Profiles are then drawn across each section. The scale of altitudes varies at each section on account of the perspective.

The main rivers are drawn in through the notches in the profiles, then the tributary streams, sea coast, cliffs and the profiles along the sides. With the profiles and the rivers as a guide to the configuration, the surface and other details are sketched in freehand.

There remain the geological sections and the indication of outcrops on the land surface. A simple structure has been chosen in this example. The only bed making a marked outcrop is the limestone band which is prominent on the cliffs and at points indicating a V-shaped outcrop up the valleys at about the 20 contour. This band would, of course, be well marked on the original map and is sketched in by reference to the profiles.

For a more complex structure outcrops can be traced on to the contour tracing and marked off in their proper positions on the profile drawing; as a guide for the side section the ends of the profiles can be used and for the front section the front profile itself.

In the case of a two-point perspective drawing the method does not differ materially. However, the initial vertical scale for heights is erected at the fore corner only and the

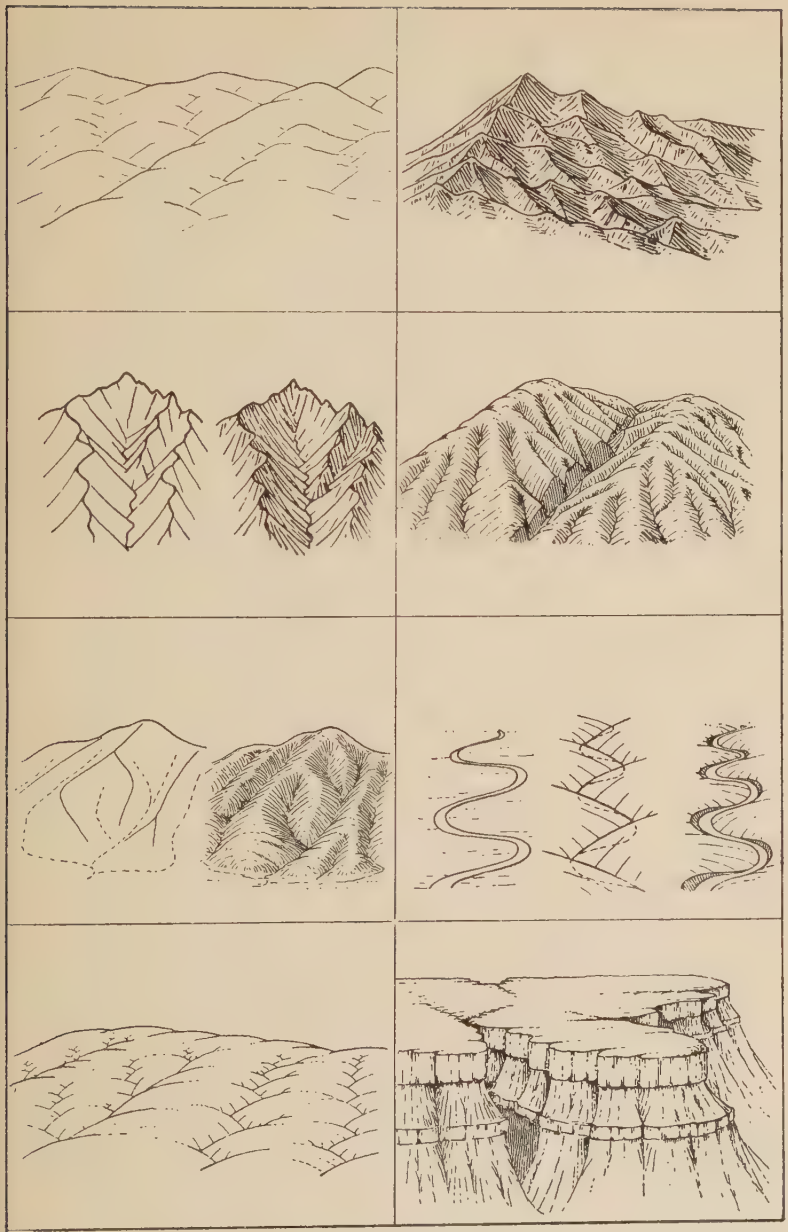


FIG. 97.—SKETCHES SHOWING METHODS OF REPRESENTING SOME TOPOGRAPHICAL FEATURES (after W. M. Davis).

scales on the four sides are built up according to the ordinary construction for perspective with two vanishing points.

It must be remembered that if the vertical scale is exaggerated the dips will also be. This exaggerated dip can be found by a simple geometrical construction. Draw a right-angled triangle whose hypotenuse makes an angle with the base equal to the true dip, produce the intercept upwards to a distance such that it is now as many times the original length of the intercept as the vertical scale is exaggerated. The new hypotenuse makes an angle with the base which is the exaggerated dip. This dip is the value to use in constructions such as that shown in Fig. 91. Often, however, it is unnecessary to go through the rather laborious construction to obtain values for angles on side sections, since the eye can be relied on to give an approximation sufficient for a satisfactory drawing.

APPENDIX I

NOTES ON EQUIPMENT AND SURVEYING INSTRUMENTS

Geological surveying, being carried out over every imaginable kind of country and in every variety of climate—in frozen arctic wastes, deserts, tropical forests or thickly inhabited and civilized countries—calls for the employment of various implements, and, after a short experience of the region to be surveyed and recognition of the particular results required, every geologist knows pretty well what he needs and what to carry about in the way of equipment. Since this book is addressed to the beginner, however, the following notes are given as a guide.

Assuming, first, that one is about to work in a civilized country where perfect maps are available on almost any scale, very little amplification of one's topographical map will be necessary. What may be required can easily be effected by cross bearings by compass, or traversing, and by Abney Level.

What are more or less essential for geological mapping are: Map, hammer, compass and clinometer, lens, notebook, pencils, coloured chalk pencils, small haversack and paper. On some days, when the work may consist chiefly in the collection of specimens, one will probably need a smaller hammer with a pick end, cold chisel and "nimbus." There is not much to say about the map, which will probably be on a scale of 6 in. to 1 mile. It may be carried in a proper leather mapping case, or cut into sections of convenient size and carried with a piece of stout cardboard to which it is bound by rubber bands, the whole slipping into a waterproof case. The hammer should weigh about two pounds. Whether one end of the head is chisel-edged in line with, or at right angles to, the handle, or even pick-shaped, is simply a matter of personal choice: so is the question of a long or short handle. A leather carrier, something after the style of a fireman's hatchet holder, is convenient when both hands are needed for climbing. The compass and clinometer are better combined in one instrument. There are various simple

forms to be obtained. The only point is, that the locking device for the needle should be efficient, a state of affairs hardly ever found in those offered for sale. The leather case should have a loop for fastening to the belt. The haversack should be of waterproof canvas with a compartment for the notebook and pencils, and slung by loops from the belt. Newspaper is about the best wrapping for specimens: small linen bags are convenient, but they do not give the same cushioning effect against rough handling that paper does, and half a newspaper goes farther than a dozen or so of bags. For very small and possibly delicate fossils, pill boxes of the type of small cylinders of wood bored from the solid, filled with cotton wool, are convenient. A "nimbus" is an arrangement of two haversacks whose tops are joined by straps which rest on the shoulders: the haversacks hang, one in front, the other behind. A heavy weight of specimens can be carried without unusual fatigue. Sometimes, in tropical countries, when the rocks are chiefly clays and soft sandstones, or highly decomposed, a large knife or "machete," which becomes normal equipment in the forest, is of far more use than a hammer.

In unmapped country, or where the available maps are not on a sufficiently large scale and lack detail necessary for the particular work that is required, the geologist will find it essential to make his own topographical map. The best method to employ depends so much on the nature of the country, the degree of accuracy and detail required and the time available, that it is hardly possible to give more than the barest outline here.

In open, or even in forested country, where the hills permit, a triangulation scheme should be carried out either by theodolite or plane table. The control points thus determined give accurate checks on the traverses, with compass or theodolite, which should start and end on one or other of these points. In open country detail can be filled in with the plane-table by intersection from, and resection to, these primary points, with the help of tacheometry. If it is impossible or impracticable to lay down a triangulation, recourse must be made to a system of closed traverses; that is, traverses which start from and end at the same point. In densely forested flat country this generally answers the purpose, though, in more elaborate surveys, triangulation can be effected by cutting straight lines which are measured directly by taping or tacheometry.

The plane-table is undoubtedly the best and most convenient instrument for the geologist, and has been brought to a high state of perfection in the United States and Canada. The table itself should

be about 18 by 22 inches in size: it must be strongly made and the legs should be rigid, not folding. A quick levelling arrangement, such as a Johnson or Hoffman head, though adding to the weight, is very convenient and saves much time. The alidade should be of the telescopic type with tacheometer diaphragm and a vertical arc reading from the sighting position: a Beaman Stadia Arc makes for speed. A good circular levelling bubble is all that is required for the table, vertical angles being taken accurately with the aid of the telescope bubble. The box compass may be either separate from, or permanently fixed to, the alidade: American practice inclines to the latter.

It is assumed that the geologist will have someone to carry his instrument about for him, in which case the matter of weight is not of great importance. In cases where he is working alone a smaller and lighter instrument will be necessary, and the alidade will probably be of boxwood with vane sights. In this case an Abney Level will be necessary for vertical angles.

The surveying compass, as distinct from the pocket compass and clinometer for geological readings, is of two kinds. First, when no great accuracy is required, a 2-in. prismatic *oil* compass is exceptionally convenient. Traverses along streams and trails, with pacing as the method of measuring distances, can be made with a pause of but a few seconds at each change of direction. Second, for more accurate work, a $4\frac{1}{2}$- or 5-in. prismatic compass and a steel tape are convenient instruments. One of the authors used a specially designed instrument—a 5-in. circular compass, read with a lens, above which was a high-powered tacheometer telescope with arc for vertical angles of 30 degrees range above and below the horizontal. On rough and uneven ground and in streams with deep pools, more rapid work could be accomplished than with a tape.

For work of a high order of accuracy a theodolite, for triangulation and traversing long distances, is employed, but the geologist is not called upon normally to do such work.

In preliminary and reconnaissance work an aneroid barometer is useful, but should be regarded, for height determination, as something better than nothing. The best types are supposed to give readings accurately to some 10 or 15 ft., but unless another barometer is recorded at one's base camp throughout the day at frequent intervals, an error of 100 ft. or more at different hours is probable and even with a diurnal correction the aneroid can hardly be trusted to within 50 ft.

APPENDIX II

THE PROBLEM OF APPARENT DIP

A simple graphical solution was given in the text (page 34). A proof of that construction may be given here.

Referring to Fig. 18 (page 35), the bed has an apparent dip of 1 (vertically) in 2 (horizontally) along the direction AB, and another of 1 in 1 along AC. Make AB = 2 units, AC = 1 unit. Then both B and C will be 1 unit lower than A: must be on the same level: and are therefore points on the strike line. Draw AD perpendicular to CB. Then, since CB is the direction of strike, AD must be the direction of true dip, and since D is one unit below A the measurement of AD in the same units as AB and AC will give the gradient of AD and hence the true dip.

It is important to be able to "see" the solid geometry concerned in the problem of apparent dips, and for this reason another graphic solution will be taken first.

The problem in the field may take on some such form as this. In the area only two exposures giving satisfactory dips are to be found, on account of thick vegetation, soil, drift, or some other reason. Both exposures are practically flat vertical faces in gullies, neither of the faces being on the true dip. Fig. 98 gives a representation of this. It is assumed that the dip is uniform over the whole area.

In each case the apparent dips and their respective bearings are measured with the clinometer and compass. One might make a model of the occurrence by cutting out two triangles of cardboard with these angles respectively of say, 30° and 46° and mounting them vertically on another piece of cardboard (which represents the horizontal plane) and at their correct angle apart, that is, the angular difference between the compass bearings.

This is the beginning of the diagram in Fig. 99, the sloping edges representing dips in the stratum.

It has been seen that the strike of a bed is the direction in which it outcrops along a horizontal surface, so if the larger ends of the mounted triangles are cut off so as to make them right-angled triangles and

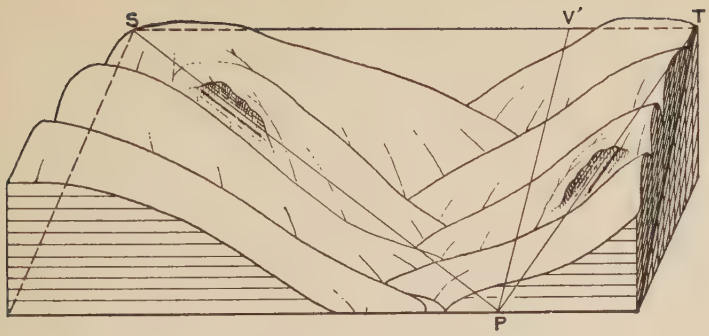


Fig. 98.—Two Outcrops showing Apparent Dip.
Compare with Figs. 99, 100, 101.

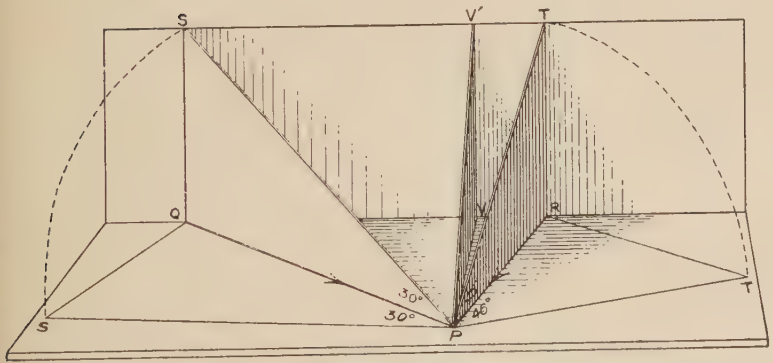


Fig. 99.—A Geometrical Model of the state of affairs shown in Fig. 98. This Figure also explains the Geometrical Construction of Fig. 100.

The triangles constructed on PQ, PR as bases are rotated about those lines as axes into a vertical position. It is easy then to picture a plane passing through P and the new positions S, T. This plane contains:—A line SP of the same bearing as QP and inclined at 30°; and a line TP of the same bearing as RP and inclined at 46°.

Then ST, a horizontal line in the plane, must be the direction of strike, and QR, its projection on the horizontal surface, also. VP drawn at right-angles to QP must be the direction of true dip. A right-angled triangle (Fig. 100) with VP as base, VV′ as intercept, placed vertically in position has its hypotenuse PV′ in the imagined plane of dip and the angle V′PV it makes with the horizontal, in the direction of true dip VP, must be the amount of true dip.

so as to make their vertical sides (SQ and TR in the figure) equal in length, a vertical piece of card of the same height placed at the back must then represent the plane of the strike. The true dip is the maximum slope and its direction is at right angles to the strike, so a third triangle, PVV′, fitted on to the model gives the amount and direction of the true dip.

To make a model to find the required quantities would be a clumsy method, although if it were worth while it would be easy to devise an arrangement of three-hinged protractors mounted vertically on a fourth as base, which would give a mechanical solution o all such problems.

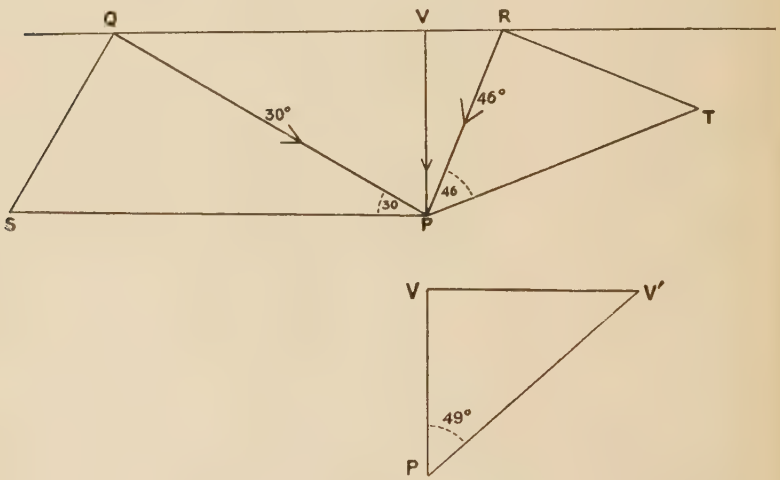


Fig. 100.—Geometrical Construction for finding True Dip and Strike, given Two Apparent Dips. Cf. Fig. 99.

Fortunately, a graphic method can be deduced from this model, as follows (Fig. 100).

PQ and PR are the two apparent dips, the bearings and amounts having been measured in the field. Plot the two bearings from any point P. From P draw (i) PS at the apparent dip angle, 30°, to PQ, meeting a perpendicular from Q at S, and (ii) PT at 46° to PR; T being a point such that a perpendicular drawn from it to the line PR is equal to QS. Join QR which represents the projection or plan of the backing SV′T used in the model and gives the direction of strike. PV drawn perpendicular to QR will be the direction of true dip.

The amount of the true dip is found by constructing a right-

angled triangle PVV′ (which can be done over the other one but in the figured is drawn separately for the sake of clearness). In this triangle VV′ is made equal to QS and the angle at P is measured with a protractor, proving to be 49°.

This graphic method is simple, but it involves careful measurements and drawing with a protractor, and with low angles of dip it is not easy to be accurate, unless the angles are set out with a table of tangents or chords and the construction is made of large size. If the horizontal angle between the apparent dip directions is small the solution is not very trustworthy.

The trigonometrical solution is as follows. Using the same example as before and the lettering of Fig. 100, assume the bearing

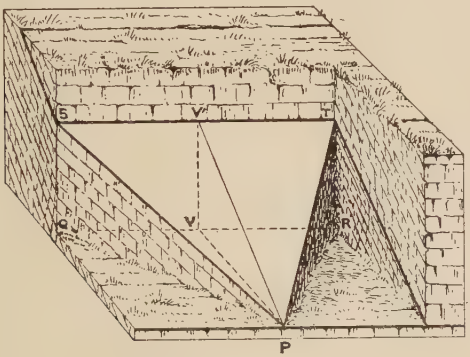


FIG. 101.—VIEW OF A QUARRY WHEN A BLOCK HAS BEEN HEWN OUT WITH ITS UPPER SURFACE A THIN WELL-MARKED BAND IN THE LIMESTONE. THE STATE OF AFFAIRS IS COMPARABLE WITH THAT SHOWN IN THE GEOMETRICAL DIAGRAM, FIG. 99.

of the two apparent dips as 200° and 286°, giving an angle of 86° between them. First find the direction of true dip, for which purpose the angle between the apparent dips will be called $2a$. That is, the angle QPR $= 86° = 2a$. Then the angle QPV which has to be found may be called $a + b$, b being as yet unknown, and the angle RPV will be $a - b$. Call the apparent dips d and d'. Then

$$\tan b = \frac{\sin (d - d')}{\sin (d + d')} \cot a, \text{ or } = \frac{\sin 16°}{\sin 76°} \cot 43°$$

from which it is found that $b = 17°$ nearly.

Therefore the bearing of the true dip is $200° + 43° + 17 = 260°$. The expression to find the amount of the true dip, D, is:—

$$\tan D = \frac{\sin (d + d')}{2 \cos a \cos d \cos d' \cos b} = \frac{\sin 76^\circ}{2 \cos 43^\circ \cos 46^\circ \cos 30^\circ \cos 17^\circ}$$

from which is obtained $D = 49^\circ$.

With four figure log tables the computation of similar examples will be found to take less time than the graphic method.

The converse problem is often presented in mining and quarrying

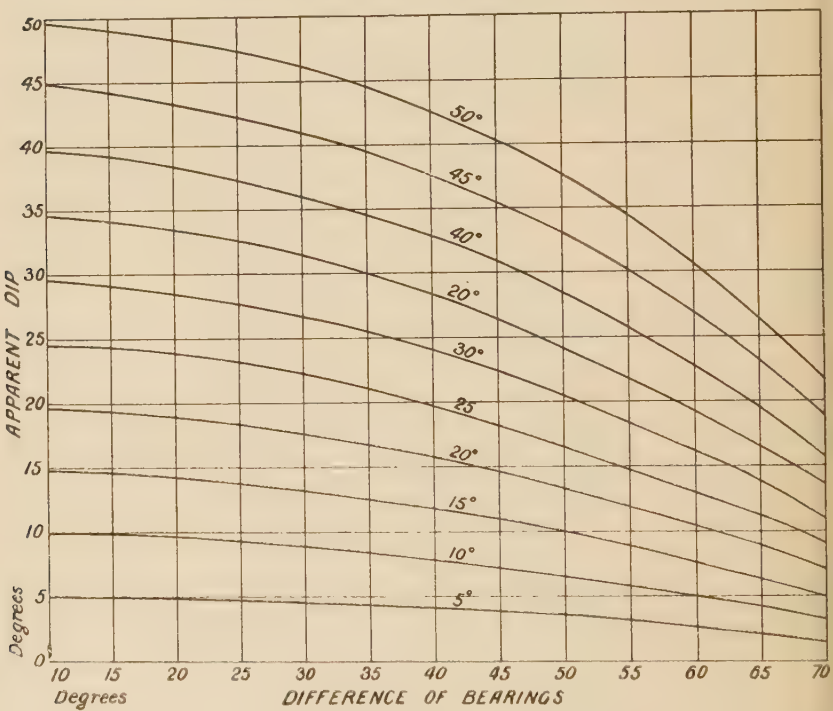


FIG. 102.—TO FIND THE APPARENT DIP IN A GIVEN DIRECTION WHEN THE TRUE DIP AND ITS DIRECTION ARE KNOWN.

The Curves represent True Dip. To find the Apparent Dip follow the co-ordinate for the difference of bearing up to the curve of the True Dip and read its Apparent Dip on the Vertical Scale.

and occasionally to the field geologist: to determine the apparent dip in any direction when the amount and bearing of the true dip is known. This case will arise not only in the field but in the drawing office when a geological section has to be drawn to scale and the line of section does not run parallel to the direction of true dip.

The graphic solution can be evolved simply from the figure representing the model, the true dip triangle being known in this case

and one of the apparent dip triangles having to be constructed, but direct calculation by trigonometry is simpler, the formula being:

tan Apparent Dip = Cosine Difference of Bearing × tan Angle of True Dip.

When only an approximate accuracy is required, as is usually the case in drawing sections to scale, it is simpler to extract the value from a graph of the above expression such as is given in Fig. 102.

It may be noted here that in drawing geological sections attention must be given to the exaggeration of the vertical scale with respect to the horizontal, such exaggeration being necessary in order to show the surface relief. The dips of the strata must be increased proportionately, that is to say, the *tangent* of the dip angle must be multiplied by the exaggeration factor to give the *tangent* of the dip angle to be plotted, not the angle itself.

APPENDIX III

DETERMINATION OF DIFFERENCES IN LEVEL

The problem is one which is constantly met with by the surveyor and often enough in one form or another by the geologist: that of finding the difference of level between two points by indirect means, the points being that of observation and a specified one on the cliff face.

To do this one must find the horizontal distance between the points and the vertical angle of elevation of the one when viewed from the other: the difference of level will be the horizontal distance multiplied by the tangent of the vertical angle. Or, if the slope distance is known from measurement, the difference is that distance multiplied by the sine of the vertical angle. For comparatively

TABLE FOR DETERMINING HEIGHTS

Slope in Degrees	giving a difference in height in 1 ft. in	
	Approximately	Accurately
	ft.	ft.
1	60	57·29
2	30	28·64
3	20	19·08
4	15	14·30
5	12	11·43
6	10	9·51
7	8·6	8·14
8	7·5	7·12
9	6·6	6·31
10	6·0	5·67
15	4·0	3·73
20	3·0	2·75

rough measurements there is an approximate formula which is easily remembered: a slope of 1° gives a gradient of 1 in 60, or more accurately of 1 in 57·3. Expressed otherwise, the tangent of 1° is nearly $\frac{1}{60}$ or ·017 and up to about 10° the tangent increases nearly proportionately to the vertical angle, so that the table on page 162 can be made up.

It is seen that the error from the approximate formula is only about 5 per cent. for 10° but rises to 9 per cent. for 20°. If 57 is used instead of 60 the error will be negligible for general purposes. To illustrate the use of the table take the particular case of a vertical angle of 4° over a distance of 300 yards. From the table it is seen that the rise appropriate to 4° is 1 ft. in 15 ft., therefore for 900 ft. the rise will be $\frac{900}{15} = 60$ ft.

The vertical angle is easily taken with an Abney Level or less accurately with a clinometer, but it is not always a simple matter to measure the horizontal distance, unless one can pace to the base of the cliff or pace part of the distance and estimate the rest. Usually an approximate measure to within 10 per cent. or so of the truth is sufficient, but if greater precision is required and the base of the cliff is inaccessible the horizontal distance must be determined by some form of rough triangulation such as those given in Figs. 103 and 104.

To find the horizontal distance of an inaccessible point by linear measurement (Fig. 103).

At A, the station from which the horizontal distance is required, set out a line at right angles to the direction of the point X. This can be done fairly well by estimation, but preferably by the use of a tape and the 3-4-5 rule as shown in the inset. Measure along this line a distance of, say, 200 ft. to C, putting in a peg or staff B half-way. At C set out another line at 90° and away from the point X: walk along this new direction until the point X and the staff B appear in line with one another. Mark this point D; then CD is equal to the required distance and can be measured.

Instead of putting the staff half-way between B and A, it can be put in at any other fraction, say $\frac{1}{4}$, when the similar triangle will be altered in proportion.

To find the horizontal distance of an inaccessible point with a compass (Fig. 104).

Take the bearing of the point X from A, the station at the end of the distance required—suppose it to be 340°. Set out a right angle

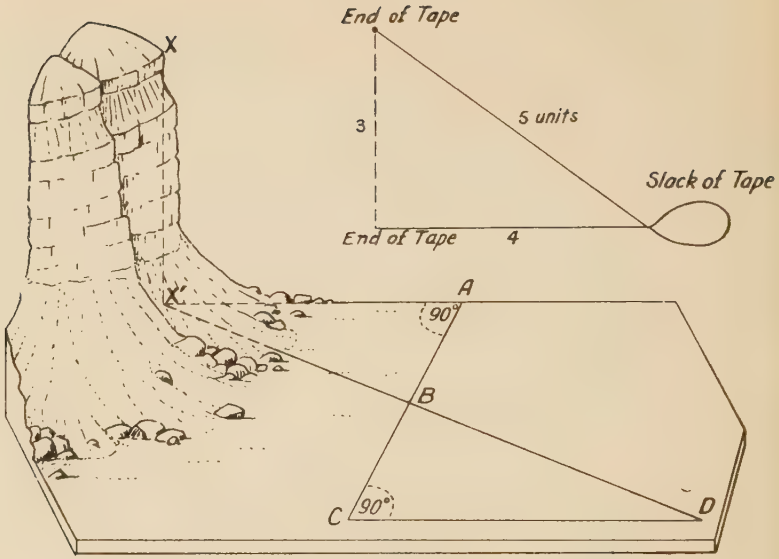


Fig. 103.

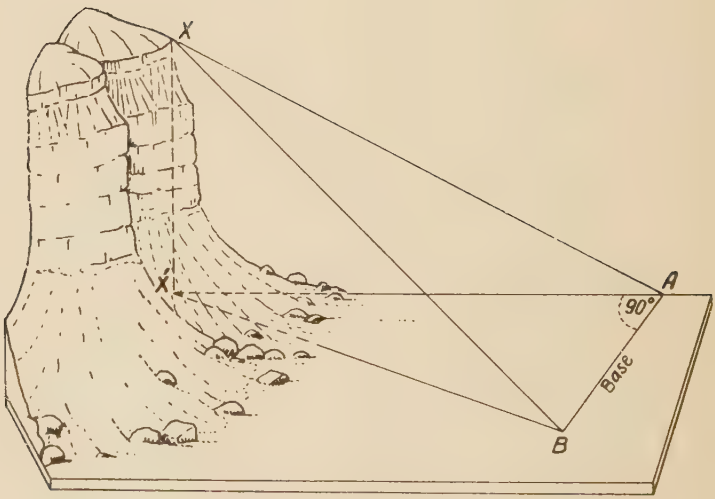


Fig. 104.—Determination of Inaccessible Points.

from A by sighting the compass along the bearing 250°: that is, 90° less than the first bearing. Lay out a base along this line by pacing or taping of, say, 300 ft. Take the bearing of X again from the end of this base, B. Suppose it to be 330°, then the horizontal angle at B will be $90° - (340° - 330°) = 80°$ and the horizontal angle at X subtending the base will be 10° Then in the horizontal triangle AX′B.

$$\frac{AB}{AX'} = \tan 10° \text{ or } \frac{300}{\text{required distance}} = \frac{1}{6}$$

Required distance = 1,800 ft.

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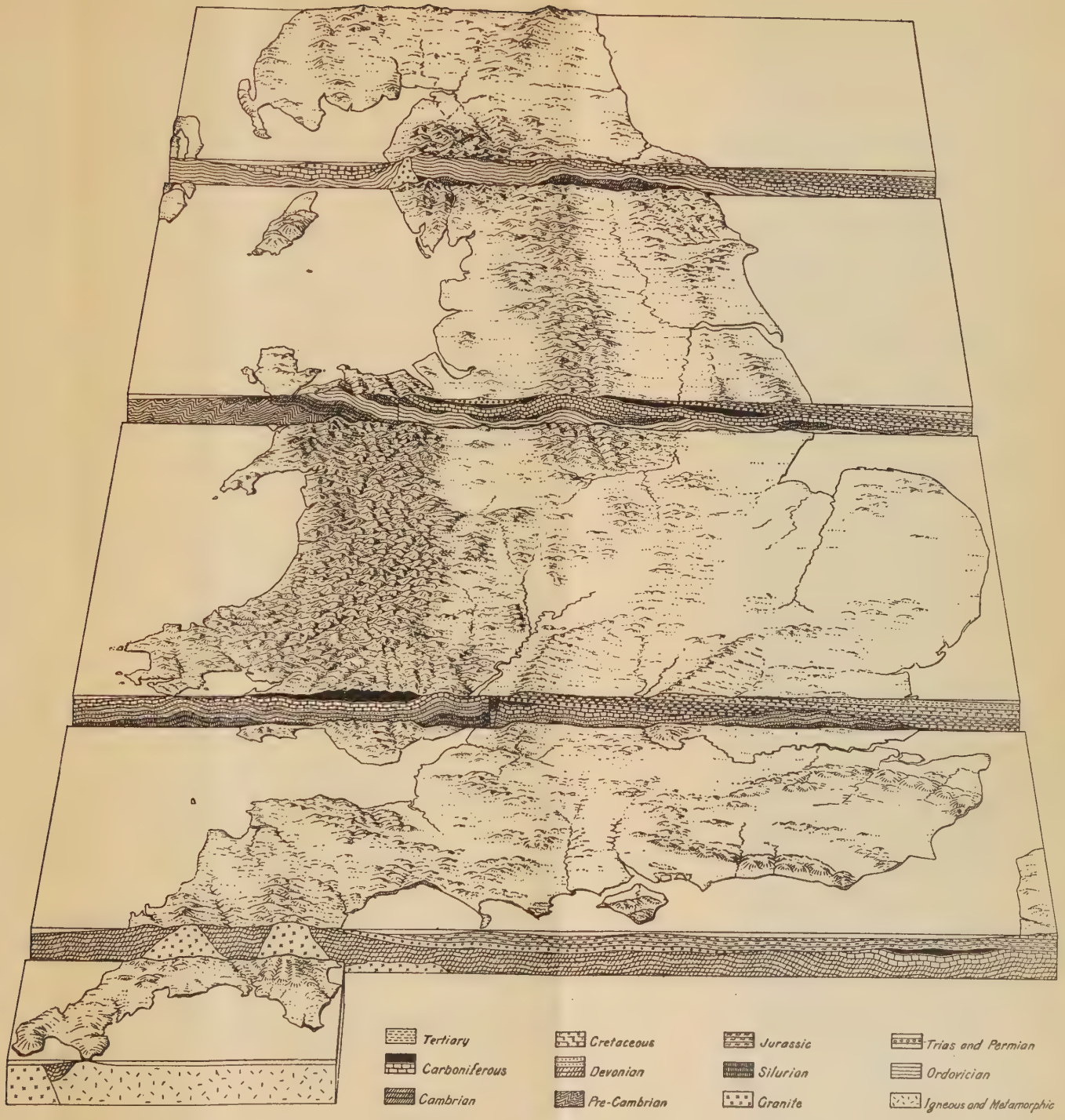

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